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Unmanned Ground Vehicle (UGV) Lessons Learned

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EXECUTIVE SUMMARY

This report compiles *Lessons Learned* from several unmanned ground vehicle (UGV) programs that could be relevant to the objectives of the Very Shallow Water (VSW) Mine Countermeasures (MCM) and Explosive Ordnance Disposal (EOD) Unmanned Underwater Vehicles (UUV) program.

Lessons Learned were collected from over 50 experts within the UGV community, through interviews and reviews of published work. *Lessons Learned* were also inferred from an analysis of the evolution of certain UGV efforts. The *Lessons Learned* are organized and presented in this report within three general areas: operations, programmatics, and technologies.

The recurring operational *Lessons Learned* involve issues of control unmanned vehicles operating among and in collaboration with humans. Aside from the technological deficiencies of onboard information processing, and of the persistent use of open-loop sensing in teleoperated and supervisory controlled vehicles, the difficulties in control result primarily from communication problems. Most control strategies now depend upon communications, and communications are undependable, because there are many vulnerabilities in its chain, including the likelihood of jamming in tactical situations. The problems of communications and control, common to the UGV environment, are exacerbated for VSW mine countermeasure tasks by the opacity to radio frequency (RF) energy, multipath for sound, and other sources of noise in that environment. Control remains a significant operational problem on land and in the water.

The recurring programmatic *Lessons Learned* involved the management of customer expectations and the definition of useful products, both of which generally exceed the prevailing technological possibilities and, as a consequence, limit opportunities for funding. Involving the user/customer early in the development cycle, often through operational testing of prototypes, successfully shaped expectations and defined and developed a few feasible applications. Because robotics applications are new to the operational environment, it is important to provide useful products in the beginning that will engender user acceptance of the technology and facilitate the necessary research and development (R&D) to provide the required capabilities.

The recurring technology *Lessons Learned* clustered around the problems of making sense out of the available onboard sensor data to automatically generate appropriate UGV control commands. Human perception, which permits successful teleoperation, is beyond the capabilities of contemporary machine perception algorithms. The workaround solutions generally have involved non-human mechanisms (i.e., short-range sound navigation and ranging (SONAR) for automatic object detection in-doors, mid-range laser detection and ranging (LADAR) for automatic object detection, the global positioning system (GPS) for automatic localization out-of-doors, tags for cooperative target recognition, and the restrictions of movement to navigable pathways in both environments). Few of these methods are likely to work underwater. However, for VSW/surf-zone (SZ) operation, in addition to SONAR, chemical and tactile detectors may be used for mine detection, localization, and classification, if further research and development investments are made.

Following our presentation of the *Lessons Learned* from those UGV experts that we had an opportunity to interview, we took editorial liberty and presented near the end of this report10 issues that we feel deserve greater attention in the robotics community. These issues probably will not attract universal agreement. They represent an alternative view of the situation. As a counterpoint, our 10 issues may stimulate dialogue essential to the discovery of new solutions to the persistent problems that the reader will find evident herein.

The top 10 issues are as follows:

Uncertainty promotes survival. Whether robots are used in logistical support, in reconnaissance, surveillance, and target acquisition (RSTA) support, or in tactical force projection, they must be survivable. An adversary that is uncertain of the robot's next move is less likely to prepare an appropriate countermove. Operators, however, prefer to accurately predict and control the behavior of their robots. While this provides advantages for safe—if limited—operation among friendly forces, predictability has definite disadvantages for operation among hostile forces. Therefore, a degree of uncertainty must be inherent in robot controllers for those robots to be successfully used in tactical operations.

Uncertainty also promotes perception. An indeterministic controller (based on fuzzy logic and bi-directional mapping) is uncertain to itself as well as to observers, permitting the construction of internal hypotheses or expectations. These hypotheses drive behavior. Self-certainty is improved, without sacrifice to survivability, through the processes of feature prediction precedent to—and validation consequent to—self-generated behavior. Therefore, a degree of uncertainty must be inherent in robot controllers for those robots to be successfully employed in uncertain environments.

Many simple cooperating agents are superior to one complex agent. The superiority of large numbers has always been valid in military affairs. It is based on inviolable physical principles. It applies to natural organisms, and will apply to robotics as well. The downside in using large numbers of robots in the military context is in the difficulty of control. Operators will be wary of such agents when control is a question. New operational doctrine will likely be required to accommodate many robot agents in a tactical environment. New methods for multi-agent coordination will be required to effectively apply many simple robots to any task currently performed by humans. For this reason, there is a high program risk to the early dependence upon multi-agent coordination for prosecution of the VSW MCM task.

New technology forces changes in operations. The military community tends to view technology as an enabler of operations, but history has demonstrated repeatedly that new technology is a transformer of military operations. As new technology forces changes in operations, it is preferred to force those changes upon our adversaries, and for developers and users first adapt to them. Thus, developers and users must remain alert to the opportunities for operational change that would be permitted and required by introducing different robotic technologies.

Understanding between the user and the developer is critical. Successful programmatic decisions cannot be made without the program office/developer and the user acquiring a comprehensive understanding of each other's constraints, capabilities, and expectations. The user has come to the program office with a problem because old methods of operation, supported by old technology solutions, no longer work. To accomplish a new solution, the

developer must understand the application and offer new technologies that improve operational efficacy, while the user must understand the proposed solution, and adjust his methods of operation accordingly. The optimal solution is a result of the combined contributions from the developer and the user.

Understanding the technology is cost-effective. Because the natures of the end-state solutions to the VSW/SZ MCM problem are not known with certainty, successful programmatic decisions cannot be made without a comprehensive understanding of the evolutionary possibilities of the supporting technologies. The program office must maintain a continuous survey of the emerging technological capabilities in all areas of relevance to the problem. This knowledge should enable the program office to pursue the most promising long-term investments.

Simpler solutions provide better foundations. Our definition of a simple solution is that process that meets a few of the requirements without violating any of the other requirements applicable to the system in which it resides. By contrast, a complicated solution is that process that meets some of the requirements while integrating badly with more traditional solutions to the remaining requirements. Requirements may be added to the solution only as long as the principle of simplicity is maintained. Natural selection in evolution is the model for this process.

Integration is not easy. When humans pick up a tool, whether the tool is a new transducer of environmental emissions like an infrared (IR) camera, or is an old force multiplier like a lever, the tool is used through the existing innate capabilities to process data to and from our five senses and many muscle groups. When we attempt to provide similar tools to a robot, that is, when we attempt to integrate some function, we face two difficulties: (1) the robot has little if any innate capability, and (2) the robot has little or no capacity to adapt to the new tool. Thus, the robot is to some extent redesigned with each addition of a tool. This redesign is the fundamental problem of integration. The difficulties of integration would be minimized if the robot employed an existing interface to use new tools, and if the robot could cooperate through adaptations of its control algorithms. These adaptations are a proven method of vertical (hierarchical) integration. Robotics developers should first identify and implement task-independent, adaptive, and general-utility core capabilities in the robot. The core capabilities should then facilitate the incorporation of unique tools designed to address the special circumstances of the assigned tasks and environments. There is a significant program cost risk in pursuing solutions that do not integrate vertically.

Communications are not dependable. Even under the best of circumstances, wisdom dictates a judicious independence from communications. Humans get by with very low capacity and low reliability communications for this reason. The most useful robots will demand the least from humans during task performance. Autonomy will be necessary to permit the low levels of communications that will be available. Robotics developers should explore technology and operational solutions that capitalize upon local autonomy and reduce communication requirements. There is a significant operational risk in a dependence upon communications, including satellite communications that serve the GPS.

Automaticity is not autonomy. Implementing automatic processes on a robot can reduce the decision-making requirements of the human operator, but risk functional failure when the control algorithms that govern the automatic processes have not been designed for the

prevailing conditions that either generate or require a response. It should be very difficult, if not impossible, for programmers to provide for every exception in critical stimulus conditions for which a novel response will be required. *Autonomy results from the self-modulation of responses (reflexes) that impact conditions in the internal and external environments, based upon the confluence of factors prevailing in both, following rules that promote the integrity and well-being of the agent*. The criterion for successful autonomy is survival, for which all novel responses are ultimately organized and executed. If survival is not a required mission or task objective of the robot, then its processes, while automatic, will not be autonomous, and the robot will likely fail as soon as the operating conditions deviate from the designed range of its automatic mechanisms. Developers should first provide application-independent autonomous capabilities for their robots. These capabilities will establish the necessary basis for the evolution of systems capable of dealing adaptively and appropriately with complex and unpredictable environments.

The road from teleoperation to autonomy does not exist. The road from teleoperation to automaticity probably does exist, but automaticity is not autonomy. The mechanisms of autonomy are fundamental and are re-expressed at all higher levels of the control architecture of an autonomous system. They are bypassed only in pathology and disease. If robot autonomy is our objective, and if humans remain in the robot control loop, then inadequacies in our robot control algorithms will be masked, and we will continue to build upon a false foundation to achieve autonomous capabilities. We should not attempt to follow a roadmap from teleoperation through semiautonomous to autonomous capabilities, for that road does not exist in reality. Rather, we should develop capabilities of fully autonomous, though behaviorally simple, robots from the onset, following the principles of autonomy outlined herein. But to do this, we must start with the simplest of tasks and add task and behavioral complexity only to the degree that autonomy is not compromised.

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1. INTRODUCTION

1.1 PURPOSE

The purpose of this effort is to compile *Lessons Learned* from the unmanned ground vehicle (UGV) programs that could be relevant to the objectives of the Very Shallow Water (VSW) Mine Countermeasures (MCM) and Explosive Ordnance Disposal (EOD) Unmanned Underwater Vehicle (UUV) program.

Even though the operational environments of the UGV programs and the UUV program are significantly different, *Lessons Learned* could save the VSW MCM UUV program considerable time and resources.

The domain of relevant *Lessons Learned* could include program management and contracting, operational concepts, sensor processing and navigation control software, multi-vehicle coordination processes, and other related robotics technologies.

All of the above issues each fall into one of three general subject areas:

1. Operations
2. Programmatics
3. Technologies

Operations deals with the use of the agents in the assigned tasks and mission environments. Generally, operations will involve the cooperation of robotic agents and human operators who currently performed the tasks, and who will either collaborate in the tasks, or will perform other tasks in the same mission environment.

Programmatics deals with the process of defining, funding, designing, producing, testing, defending, supporting, disposing, and certifying the robotic agents for the intended tasks and missions.

Technologies are the broad range of capabilities that support the robotic agent in the performance of its tasks and missions, including power, communications, sensors, actuators and effectors, control algorithms, and computational hardware.

We present herein *Lessons Learned* as reported by prominent members of the UGV development community in each of three general subject areas defined above, interspersed with our own editorial opinions on the issues.

1.2 APPROACH

1.2.1 What are *Lessons Learned*?

We presume that *Lessons Learned* are the conscious and communicable awareness of the consequences of different actions, where some consequences are approved while others are regretted.

1.2.2 Where can we find *Lessons Learned*?

Lessons Learned are often acquired by trial-and-error experience, and then written down by the considerate developers and users of robotic systems and published for the benefit of others. We, therefore, sought out and studied these informative publications.

More often, however, *Lessons Learned* are the essence of experience, and are indirectly acquired by the inexperienced only by enrolling in formal courses of instruction. To gain the benefits of others' experience outside the classroom, we must persuade each teacher to provide a private tutorial. This we have attempted to do through personal interviews.

Most often, however, *Lessons Learned* remain as unconscious or undocumented solutions to problems that no longer recur in the particular developmental effort. They warrant no further attention, and disappear from consciousness. The only way to recover these *Lessons Learned* is to examine the evolution of the product and reconstruct the problems and their solutions from the design or procedures that are presently working.

For example, in earlier times, when man fought with horse, lance, arrow, and sword, the fortified castle proved to be an effective method of defense for a disadvantaged population. By observing the operational use of castles under threat conditions, we could infer that the defenders had learned that high thick walls improved their chances for survival. With the introduction of gunpowder, this lesson was no longer valid. Castles crumbled and new lessons had to be learned. One such lesson was that the faster one moved, the less likely one would become a target. Mobility and maneuverability then resumed dominance in military tactics.

The behavior of the practitioners, as much as their tutelage, can inform us of the lessons that they have learned. We have therefore added commentary to our compiled listing of admitted *Lessons Learned* that analyzes aspects of the behavior of the robotics developers and users. This commentary represents our assessment of the factors that have driven and may continue to drive the development and application of UGVs.

1.2.3 Sample Domain

We identified robotics experts in government, academia, and industry primarily by reputation. We sent e-mail to these individuals for their *Lessons Learned*, and followed those requests in most cases with telephone calls to complete their interviews. Other experts were referred to us by our original list of contacts, and our information gathering process was repeated with those referrals. We regret the omission of other prominent robotics experts with whom we failed to make contact.

1.2.4 The Returns

In the time allotted for data collection we received hundreds of *Lessons Learned,* contributed by over 50 experts in robotics technology development and robotics program management, that are potentially relevant to the development and employment of small unmanned underwater vehicle systems in the VSW MCM mission. The scope of the *Lessons Learned* is apparent from the fourth level of the table of *Contents* of this document, while Section 6 lists all cited contributors.

Table 1 lists the Government Program Offices, Government Laboratories, Academic Institutions, and Commercial Enterprises from which we received those *Lessons Learned*.

Table 1. Organizations contributing *Lessons Learned*.

Program Offices	Other Gov.	Gov. Labs	Academic Labs	Commercial
UGV/S JPO (*RCSS, SRS, Gladiator, MPRS, TUV, Viking*)	**IDA**	**NIST** (*XUV*)	**WHOI** (*REMUS*)	**SAIC** (*XUV*)
TARDEC (*XUV*)	**NAVSEA**	**Sandia** (*Hagar, Hopper*)	**USC** (*SCOWR, MARS, Urbie*)	**Titan** (*SRS*)
PMS EOD (*BUGS, RONS*)	**DTRA**	**SSC SD** (*MDARS-I, MDARS-E, MPRS, AUSS*)	**CMU** (*Gyrover, Urbie*)	**GDRS** (*MDARS-E, XUV*)
AFRL (*ROCS, ARTS*)	**OSD**	**JPL** (*MARS, FIDO, Urbie, Nanorover*)	**Georgia Tech**.	
PSE (*MDARS-I, MDARS-E*)	**TRADOC**		**MIT** (*DARTs*)	**iRobot** (*ALUV, DARTs, Fetch II, Urbie*)
ARL (*UGVTEE, XUV, FCS*)				
DARPA (*MARS, TMR-Urbie*)				
NSF (*SCOWR*)				
ONR (*Gladiator*)				

Robotics products are indicated in italics. Organizations with robotics experts contributing *Lessons Leaned* are indicated in boldface type

1.3 ORGANIZATION OF THIS DOCUMENT

This report is organized as follows. Section 2 discusses some of the operational factors that contribute to the present VSW MCM mission. Section 3 lists open issues and outstanding difficulties in VSW UUV technology and operations. Section 4 catalogues and elaborates on specific *Lessons Learned* from the UGV community. Section 5 summarizes 10 significant issues arising from the *Lessons Learned* and offers recommendations to the VSW MCM UUV Program Office. References and sources cited are listed at the end of this report. Appendices provide additional information for reference.

The presentations of UUV open issues and UGV *Lessons Learned* in Sections 3 and 4 respectively are organized along the three subject-area categories listed above, and at a second level, along specific issues of program office concern. This organization is for convenience of presentation only, and does not imply any independence of operational, programmatic, and technological issues. Where obvious dependencies exist, we will try to note them.

In the following three sections, information that comes primarily from either transcriptions of interviews with experts or from extractions of published material, are indicated by references and by 1/2-inch indentations of text. Each reference includes the originator's last name and source date in boldface font **[…]**. The originator's full name, source, and contact information are available in Section 6. The editors freely introduce and provide commentary upon the referenced *Lessons Learned* with material that is neither referenced nor indented. This material should be considered as editorial opinion.

2. The VSW MCM Mission and Environment

2.1 SOURCES OF INFORMATION ON THE VSW MCM MISSION AND ENVIRONMENT

The Office of Naval Research (ONR) released a Broad Agency Announcement (BAA) in February 1998 to solicit studies of systems and technologies that would support manned and unmanned VSW MCM missions. With this BAA, ONR provided online an information paper that summarized the VSW MCM mission and its environment **[ONR, 1998]**.

A recent published source for information on the VSW MCM environment is *Oceanography and Mine Warfare.* This publication is also available online **[NAS, 2000]**.

An operator's perspective on the VSW MCM mission is available in the Proceedings of the 4th International Symposium on Technology and the Mine Problem **[James, 2000]**.

2.2 KEY CONSIDERATIONS ON ENVIRONMENT, PROCEDURES, AND TECHNOLOGY

The following paragraphs, outlining the current environment, procedures, limitations, and technology, were provided by ABHC Scott Trieble, the sole member of the UUV platoon of the only existing VSW MCM detachment in the U.S. Navy.

2.2.1 Operational Environment

> *Very shallow water* (VSW) is defined as that expanse of water proximate to the shore-line with a depth of from 40-10 feet. The *surf zone* (SZ) is defined as the remaining water from 10 feet of depth to the beach. The VSW/SZ contains a variety of obstacles including rocks, kelp, and eelgrass. Visibility is typically from 0-5 feet in the daytime. Buoyant objects are subject to significant back-and-forth surge currents. The slope of the shelf to the beach is uncertain and locally variable. Depending upon the slope, the range between the possible locations of hostile forces on the beach and the locations of MCM activity in the VSW/SZ can be from a few yards to a few thousand yards. [**Trieble, 2001**]

2.2.2 Current Procedures

> VSW MCM operations are accomplished at present using a combination of marine mammals and human divers. Dolphins locate potential mines using endogenous sonar, then drop pingers to tag locations. Human divers must reacquire the locations by orienting to the pingers. The human divers then attempt to visually identify the objects. If the objects are mines, the divers place timed charges and move on to the next pinger. The Navy typically does not employ marine mammals and divers in the SZ. Brute force neutralization by the laying out of a blanket of charges is used there for in-stride breaching, although the breaching of obstacles in the surf zone is still problematic. [**Trieble, 2001**]
>
> The mine-hunting/clearing operations are carried out during nighttime because the dolphins must be brought in by small boat, which would be at greater exposure to hostile fire during the daytime. Human divers carry small chemical lights to use in

mine identification. If marine mammals are not available, the human divers can locate mines using the AN-PQS2alpha hand-held sonar unit. Human divers have a lot of gear to carry, including mine neutralization charges and the pinger localization or sonar equipment. Deployment of divers by submarine is generally not feasible because the deeper waters in the approaches to a possible mined landing sight are also mined, and must be cleared by other means prior to submarine transit.

The size of the present VSW MCM Detachment is approximately seventy personnel. Forty are in operations (mostly diver qualified), eighteen go into the water, twenty-one service and control the dolphins, and six will operate the UUVs. [**Trieble, 2001**]

2.2.3 Current UUV Technology

In June of 2001, the VSW MCM Detachment received and began operating two underwater remotely operated vehicles. These vehicles are variants of the Woods Hole Oceanographic Institute (WHOI) Remote Environmental Monitoring UnitS (REMUS).

Figure 1. WHOI REMUS vehicle.

REMUS is a low-cost autonomous underwater vehicle (AUV) developed by the WHOI Oceanographic Systems Laboratory for coastal monitoring and multiple vehicle survey operations **[WHOI]**. The REMUS vehicle weighs 120 pounds, is powered by lithium-ion batteries, and can be deployed and recovered from a small boat by two people. It navigates by orienting to a grid defined by pre-located pingers, which may be placed by divers or surface craft. The vehicle locates mines using side-scanning sonar. A map is created by downloading sensor data only upon recovery of the vehicle. The vehicle has no obstacle avoidance capability, so it can be lost upon collision with an obstacle. [**Trieble, 2001**]

2.2.4 Limitations of Current Procedures

> Mine countermeasure operations are extremely hazardous to personnel. The underwater environment, even without the presence of lethal explosives, is unforgiving. Cold water limits the time divers may operate. Buried mines cannot be located. Once set, the clocks in the mine neutralization charges can neither be reset nor suspended. There is no capability to remotely synchronize the activation of the charges. [**Trieble, 2001**]

Nighttime operation, necessitated by the likely presence of hostile forces near the beach, significantly reduces visibility, defeating man's primary sensory capability. Passive IR and other night-vision equipment, which are relatively inexpensive and widely available, could expose the small boats and divers and eliminate the night operation advantage. Sonar receivers and/or bioluminescence products, if placed in the minefields, could detect the operation of the marine mammals and human divers.

The present UUV (REMUS) requirement for pre-placed acoustic grid markers imposes an additional burden upon human operators. Loss of function of any acoustic grid marker could disable the mapping capability of the UUV.

3. OUTSTANDING ISSUES FROM PREVIOUS UUV EFFORTS

This Section presents questions and unresolved issues from previous UUV efforts in an attempt to highlight the pressing operational problems and technology needs that might be unique to the VSW environment.

3.1 UUV OPERATIONS

3.1.1 A UUV Concept of Operations in VSW Reconnaissance Missions

It is often useful in any investigation, though often a little irritating, to start with a few questions. These questions must go beyond the simple "what is the problem?", for to solve any problem, one must know something of its mechanisms or contributing factors.

But first, let us begin with a restatement of the problem.

> It is cheaper to build a mine than it is to build a countermeasure, and faster to build a new mine than a new countermeasure. The miner seems to have the advantage in staying ahead in this loop. **[Jones, 2000]**

Amphibious landings have been effectively practiced since at least the time of Homer, and probably go as far back as the invention of the boat. The defenders of the beach have used missiles, obstacles, and fire to discourage those landings. Today, mines of all types, placed in sequence from deep water to beyond the surf line, make the transit from the deep water to the land very hazardous. The mines can detonate on contact and on approach using various clever sensors. As it is physically difficult to mask one's signature and harder still to be immaterial without first encountering a mine, the mine seems to have the tactical advantage.

Since mines are themselves material, the standard approach has been to exploit the mine's signature and after detecting it, to avoid it, or to neutralize it. Our objective has been to develop better signature-recognition devices in our MCM equipment than the opposition forces have in their mines, thus getting inside the opposing information loops. One difficulty, however, is that the mine's reason for being is to self-destruct upon recognition of its target. The mine can afford to make one false positive error, but we cannot afford to make one false negative error. Again, the mine seems to have the advantage.

Is there a way to use the nature of the mine to our advantage? Or, to put the question another way, is it always operationally appropriate to activate or neutralize a mine just before our advance through the field? We could, for example, under certain circumstances, find it expedient to activate or otherwise neutralize mines as they are laid. Just a few seemingly random and ill-timed activations could significantly disrupt the mine-field seeding operations. This disruption would require a pre-deployment of the MCM agent. But, however we answer that question, we still must detect and neutralize a mine.

Following are a few other relevant questions on detection and neutralization:

Some preliminary questions on *Detection*:

- ✓ Is the system required to detect individual VSW mines or is the concept to clear a path without necessarily detecting individual mines? I think the JAMC program was doing the latter at least on the beach.
- ✓ If detection of individual mines is required, do we know what sensors can accomplish this with high reliability, the characteristics of these sensors, and the operating conditions necessary for successful performance? The answers are likely to drive the systems.
- ✓ How can the water movement in the surf area affect detection (for better or worse)?
- ✓ To what extent can the detection process be automated successfully? [**Schwartz, 2000**]

Some questions on *Neutralization*:

- ✓ Will VSW mines be neutralized individually? At the place where they are located? If so, how?
- ✓ If not, how will neutralization be accomplished? [**Schwartz, 2000**]

Some questions on *Tactical Situation Parameters*:

- ✓ Is this a combat scenario as opposed to peacetime de-mining operation?
- ✓ If so, what constraints does (possible) enemy presence impose (e.g., on explosive neutralization)? [**Schwartz, 2000**]

While implicit in the above questions, a couple of additional questions may be raised:

- What are the schedule constraints between the deployment of the MCM assets, the verification of a clear lane, the clearance of a mined lane, and the use of either lane?
- Is it strategically permissible to discourage or prevent the distribution of mines prior to any tactical use of the lane?

Answers to the above questions can help guide the development of the concept of operations for a VSW MCM UUV.

3.1.1.1 Steps in the Mine Hunting Process

The mine-hunting/clearing process is logically divided into seven primary tasks:

1. Deployment and distribution of assets
2. Execution of a search strategy
3. Detection of mine-like objects
4. Classification and identification
5. Neutralization
6. Verification or certification of clearance
7. Recovery of assets.

To ensure that the mine clearance is complete, the sequence above may need to be repeated several times, depending upon the level of acceptable risk. The current use of dolphins for detection and divers for identification and neutralization requires that some but not all of the steps be repeated. For example, the target objects (candidate mines and obstacles) must be acquired twice, once by the dolphins and once again by the divers.

3.1.1.2 The Deployment of One Complex or Many Simple Vehicles

If only one very competent agent was assigned to accomplish the above sequence, we must assume that it would be quite valuable (as are divers and dolphins), requiring the completion of all steps through recovery, and returning the cost/benefit advantage to the inexpensive mines. The assignment of a few of such agents would not materially change this situation.

If, on the other hand, many relatively incompetent and yet inexpensive agents could be used for mine hunting/clearing, then we may not have to accomplish all the steps above. Definitely, we would need to perform steps 1 and 5, and quite likely, 6, but detection, classification, and recovery could be inconsequential if the many cheap agents could clear the lane of mines.

A Massachusetts-based company, iRobot, an outgrowth of Professor Rodney Brooks' work on subsumption architectures at the Massachusetts Institute of Technology (MIT), has developed a crab-like robot, the Ariel Autonomous Legged Underwater Vehicle (ALUV), for mine and obstacle neutralization.

> In an amphibious assault operation, a fleet of these expendable bottom crawlers are deployed to collectively search a zone. Each will find and secure itself next to a mine, then wait for a detonation signal. For non-destructive operation, modifications can be made to allow the robots to deposit an explosive in a predetermined location and move to safety before detonation. **[iRobot]**

Questions remain on how the ALUV would find the mines, maintain an efficient search of the designated lane, and find their way safely out of the search area if recovery was required.

A modification of the iRobot approach could have the ALUV-like agents distribute themselves over the lane with a density sufficient to neutralize all resident mines and obstacles. A "brute-force" approach is again contemplated here.

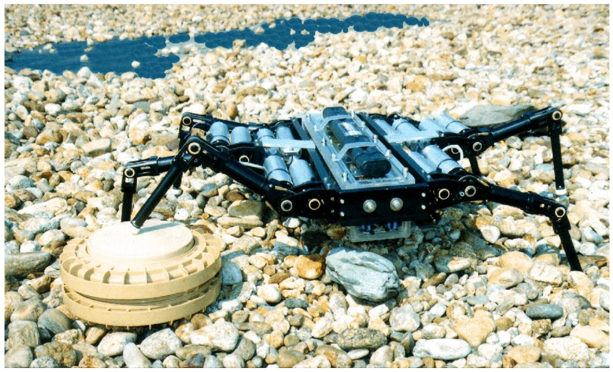

Figure 2. iRobot's Autonomous Legged Underwater Vehicle.

There are two crucial questions that must be adequately addressed with the use of all of the approaches that use sensor/capability-limited agents: (1) would the clearance be complete, and how would we assess this? and (2) what would we do with our own unexploded ordnance (UXO) that could survive this process?

There are other approaches:

> There are two possible concepts for both crawling and swimming UUVs for mine detection. The first possible concept of operations for using robotic systems in a VSW environment would be to employ a moderate number (6-12) vehicles in a collaborative mode to 'swarm' onto a target. In this concept, the UUVs have a very basic collaborative algorithm that simplifies navigation and would use a magnetic detector to help each other find the target. I'm not sure how well this would work in a multiple target environment, however. (SANDIA LABS have been doing some work in this field). The other concept is to use one or many robots to search and detect mines. In this case, each robot is independent of the others and could use a pattern or random-search methodology to cover an area. This concept would work better in a multi-target situation, and probably require fewer systems, but would require more complicated robots. **[Clemons, 2000]**

The basic question here is whether to assign one or more vehicles to the task. Since the task is distributed (there are many mines in the VSW/SZ and possibly many different types of mines and obstacles deployed), an assignment of many vehicles with different capabilities may be preferred to the assignment of one multipurpose vehicle. Task completion time can be decreased, of course, with increased numbers of resources applied in parallel. The current operational process of draping a mesh of distributed charges over a minefield in the SZ or on the beach to clear a lane is a very simple example of a distributed solution, while the current practice of using dolphins for detection and humans for classification is an example of the multi-agent approach.

The specific technical requirements for logistics, power densities, sensor configurations, communications, and control capabilities will vary depending upon how the seven primary MCM tasks are allocated among the several vehicle types. The fundamental advantages of the application of multiple agents, however, are in speed and in reliability of mission

completion, that is – in overwhelming power. The fundamental disadvantage is in cost. When costs per agent could be sufficiently reduced, as was historically the case with the common foot soldier, the economics of combat was simply *the more the better*.

But all is not so simple, for:

> It is a mistake to think that intelligent group behavior will emerge from a collection of simple robots **[Albus, 2001]**

To achieve useful, if not intelligent, group behavior from a collection of simple robots, some very smart planning and clever programming may have to be performed in advance of the deployment.

> The goal of the Swarm project at IS Robotics is to develop techniques for programming a distributed group of autonomous robots. Programs for individual robots need to be robust in the face of complex environments, and the group software needs to be tolerant to the failure of any number of individuals. The algorithms developed must be designed to be completely scaleable, that is to function with groups of 10 or groups of 10,000. **[iRobot]**

A strict either/or choice in the question of one complicated agent versus many simple agents may not be the best way to have asked the question, for there are other alternatives.

> NAVEODTECHDIV is pursuing a somewhat similar problem, namely clearing large quantities of small UXO (bomblets). They are working on two concepts, both of which involve a significant number of small UGVs operating simultaneously within a target area. The small UGVs are thought of as semi-expendable. In one concept, the small UGVs perform either a random search or a pattern search and when a UXO is found, act to neutralize it (representing a potential trade in thoroughness for speed). In the second concept, a single large UGV searches for and locates the UXOs after which the small UGVs are dispatched to neutralize them (representing a potential trade in cost efficiency and in speed for thoroughness). A variant of this latter concept might be to have the large UGV release a small UGV whenever a UXO is found. There is some interest in "marsupial" robots these days and the DARPA Tactical Mobile Robotics program has done some work in this area. **[Schwartz, 2001]**

The marsupial concept has several advantages. The "mother" robot could provide not only transportation, but also computation, power, and communications support, in some respects substituting for human support personnel.

The next Figure shows an early marsupial application involving the MDARs-E platform as the "mother" and the MPRS URBOTt as the deployable element. The gas-powered MDARS-E platform transports the battery-powered MPRS URBOT to a RSTA site where the URBOT is released to provide high-risk target acquisition and laser designation. Operators drive the remote URBOT using communications relayed through the intermediately located MDARS-E platform.

Figure 3. MDARS-E and MPRS URBOT in a "marsupial" configuration.

Another variation on the distribution of different capabilities between non-equivalent task agents follows:

> The sensing pod need not be rigidly attached to the base vehicle. Nor need the communications method. Examples could be floating antenna, pop-up cameras, vehicles could be tethered to each other in pairs or by snag lines. The principle is distributable sensors and effectors. The distributed elements may be camouflaged to appear as natural objects in that particular environment. Distributable sensors may be less expensive than moving a larger vehicle. They may be abandoned. They may provide multiple perspectives, they may not require much in the way of machinery and power. **[Schempf, 2001]**

As is often the case, the feasible solution may be a compromise between the many factors from the different domains of *operations*, *programmatics*, and *technologies*. An important lesson, however, is to try to avoid adherence to any particular solution or process model, for other solutions may be admitted following the relaxation of a constraining factor from among any of the domains.

3.1.2 Target Localization and Mapping Techniques

Mapping involves establishing both the frames of reference and the rules for transforming the locations of objects between those frames of reference. When the locations of the objects in both of the frames of reference are unknown, then methods of target localization must be developed and applied. Target localization is the first problem of mine hunting.

Looking for the mine where it is most likely to be found is a good way to start, but one must first establish a frame of reference for that territory. The absence of our customary natural frames of reference under water contributes to the difficulties we have in navigation and mapping there.

> A TOV underwater is very difficult to navigate as there are no horizon or other landmarks for orientation. Disorientation should be expected. **[Schempf, 2001]**

Thus, underwater we see no horizon, we see no GPS, we do not see very much at all. For this reason, existing operations pre-position sound-reference beacons to provide landmarks.

If this pre-positioning of reference posts is impractical for whatever reason, then what are the alternatives? One possibility could be the positioning of reference posts on the fly, that is, in the process of mapping. An agent in the beginning of a map operation might deposit its reference posts in the best configuration that it can, and then work within its own grid.

Another possibility could be that once in the area to be mapped, the diver or vehicle might "look around" with sonar to find local references. This process could succeed if there were two or more detectable sonar landmarks. Fixed obstacles would be ideal for this purpose, for they should describe a unique pattern of placement relative to the slope to the beach. Then as the agent moves through the area, it could continue to take sonar bearings from those landmarks, and with the aid of an inertial navigation system (INS) and a compass, map the relative locations of its way-points. The agent would calculate how the sonar bearings would change as it moved relative to its landmarks. The confirmation of this calculation with the actual sonar returns would tell the agent where it was located. This calculation would be a computationally intensive process, but quite within the capabilities of current technologies for either a manned or unmanned system.

Beyond the solution to the problem of navigation and mapping, one must decide how best to search the area. Possible criteria for a good search include:

- Coverage—how much of the territory is actually searched?
- Detail—how many different types of targets are catalogued?
- Speed—how quickly can the search be completed according to the two previous criteria?

Any of the search criteria can be traded in favor of the other two.

In addition, a search pattern can be governed by either one or both of two basic factors:

- Intrinsic—internal rules that plan and control the search.
- Extrinsic—external conditions that control the search.

Intrinsic factors are often considered to be intentional or systematic, while extrinsic factors are often considered to be random.

> Random search patterns are not efficient. **[Schempf, 2001]**.
>
> The environment is not random, which could defeat a random search pattern. **[Albus, 2001]**

In nature, the first sensors developed in marine animals were for chemicals, light, and gravity. With these simple sensors, agents could find and discriminate relevant targets, and orient with respect to the vertical, which facilitated navigation. To the degree that the stimuli activating those three types of sensors (and thus controlled the behavior of the animal) were regular and consistent, the animal appeared to behave systematically. Memory, a much later

addition, improved the consistency of behavior in complex (para-random) and simple environments.

The locking of the search pattern to an extrinsic event can create the appearance of randomness if the event is unpredictable, but can also create the appearance of consistency otherwise. If the object of the search provides a reliable and detectable factor, then locking the search pattern to that factor might be a good idea. Whether the pattern was random or systematic would not matter in such a case if all of the search objects were found. Counter-mine countermeasures, of course, will attempt to mask all such factors.

The information available to a tidewater UUV may be greater than our own experience permits us to presume.

> Consider multi-resolution maps: Perform multilevel planning by time frame and by other time dependent factors. Can monitor wave and tide action using pressure and flow sensors, and plan behaviors accordingly. **[Albus, 2001]**

Obviously, orienting is a major aspect of mapping. Similarly, searching is a major aspect of orienting. Some of the earliest examples of mapping in nature are the abilities of arthropods such as bees and ants to find their way to and from sources of food and the nest. These species search for key stimuli—a chemical trail, or the position of the sun. They then orient to the key stimulus and maintain that orientation during their excursions. Bees can communicate their maps to other bees. There is evidence that ants behave similarly. These species definitely depend upon group action for survival, thus maps are critical to the coordination of several otherwise independent searches. At the next level of the phylogenetic scale, however, the mollusks (snails, slugs, and octopuses) that generally live solitary lives, also use maps to navigate. We may be able to follow the suggestion of Albus by applying the elementary mapping capabilities of arthropods and mollusks to simple UUVs in the VSW/SZ. After identifying the key orienting features of that environment, the simple UUVs could then create, use, and communicate maps to their co-specifics.

3.1.3 Operational Logistics and Supportability Issues

Smaller entities tend to be less expensive under all measures of cost (yachts, dinosaurs, UUVs, and computer software are familiar examples of this truth).

> Smaller of everything (except on-board intelligence or processing capability, and on-board power) was better because support requirements were much reduced. **[Walton and Uhrich, 1995]**

Small inexpensive agents require less maintenance support because they can be replaced, but the need for replacements can add to the logistics load. Agents of the approximate size of man are easier to work on as the components may be just large enough to see with unaided vision, and just large enough to manipulate by hand. This size is an advantage if in-service maintenance is desirable. The main advantage of the largest agents is that their maintenance requirements are generally less following collisions with the smaller agents.

Obviously, the task circumstances should determine the appropriate size for an agent. Those agents, for example, that must operate in man's environment, using man's hand tools

and negotiating human spaces, must scale to the dimensions of man. On the other hand, man has developed tools across many scales, some quite large and powerful, others, quite miniature. The integration of controller and tool could result in agents at all those scales.

Small agents require refueling more often than large agents. Often, however, the low power reserve of small agents can be compensated with cooperating numbers.

Generally, the cheaper a product, the more abundant it becomes. This abundance can contribute to the VSW MCM solution and to its problem. Therefore, the proliferation of small, inexpensive, and adaptive agents must be controlled; otherwise, they will surely appear as mines.

3.1.4 Concepts of Deployment/Recovery

Deployment and recovery of UUVs in non-military contexts are not burdened by the need for covert operations, but are still troubled by all the problems of dealing with the sea and with the weather. As with other aspects of logistics, vehicle size is a factor. Smaller vehicles are easier to handle than larger vehicles. But smaller vehicles must be placed in proximity to their targets for lack of endogenous sustaining energy.

> How to address power density? Batteries do not have adequate staying power; best to avoid fighting gravity; air deployment is more efficient than water deployment. **[Schempf, 2001]**

Air deployment generally precludes covert operations and raises the question of air recovery, but it may work effectively as part of an in-stride clearance operation. After which, recovery could be accomplished at leisure.

If the agents do not have to be recovered, reserve power requirements are reduced.

3.2 PROGRAMMATICS

3.2.1 Acquisition Strategies

The commercial UUV product appears more mature than the UGV product because the undersea environment is more hostile to man, thus motivating the markets for, and then the development and production of UUVs. The opportunities for commercial participation in the VSW MCM acquisition are therefore greater. The commercial UUV industry also has a broader base favoring competition.

3.2.2 Performance Parameters and Methods for Test and Evaluation

A major problem with system-level testing in the Department of Defense (DoD) today is that we can almost never tolerate failure. Military and civil service careers, company profits, and political reputations all depend upon successful acquisition programs. Thus, measures of performance (MOP) and measures of effectiveness (MOE) are nearly always set to levels that are inversely proportional to the probability of failure of the system. As a consequence, poorly designed systems pass their tests, that is, they survive, and their very persistence contributes to the replication of their design flaws in subsequent systems. Only during total

warfare, when other careers depend upon the demonstration of the vulnerabilities of our products, does it become apparent to us what works and what does not work.

Nature has been much more efficient through the processes of evolution in funding programs; only the fittest designs survive. While one could say that warfare is pretty much continuous in nature, the most successful natural design features are still proven in that process and are reproduced again and again in all variety of subsequent organisms. Recent discoveries in the huge overlap in Deoxyribonucleic Acid (DNA) between unicellular organisms and man bear this out. Another example of the preservation of working designs in nature are the similarities in brain organization between all mammalian species, including man, but of course, the origins of those similarities are in the DNA.

A lesson from nature for developers of artificial systems could be that unrestrained "live-fire" testing should occur as early in the developmental cycle as possible, and should include efforts of opposing (Red) forces, as determined as would be real competitors, to defeat the proposed design. Then, if the design fails to survive, measure its cost of production against the costs to the enemy to defeat it. If favorable, then let it continue; if unfavorable, then let it become extinct.

But even a good design can suffer from bad production.

> Nothing substitutes for fundamentally reliable equipment **[Yoerger, 2001]**.

> Just takes extra effort, test and test again. **[Yoerger, 2001]**

> The hardest thing is to get everything to work at once: things that fail could be a latch, a motor, a connection. The underwater environment is unforgiving. **[Yoerger, 2001]**

3.2.3 System Definition

A system could be defined at many different levels of complexity or integration. The control system may be composed of programs that manage task priorities, sequencing, memory and access, and communications. The vehicle is a system of components that may include frame and chassis, sensors, motors and propulsion, energy sources, communications, and control functions. The MCM system may include the vehicle, the operators, the support craft, the navigation buoys, and the operational environment including the mines and obstacles. The architecture is one way to describe the system.

> Don't waste time talking about architecture, more reliable components are better. **[Yoerger, 2001]**

Another definition of *reliable* is *survivable* (see section 3.2.2).

> Keep computer scientists out of the project. They will build an immense software edifice and keep mucking with it forever. It will take 10,000 CPU cycles to add 1+1 and need to go at 500MHz to have the through-put to talk to a peripheral that is only a single-chip 8-bit microcomputer. Use something simple. **[Bradley, 2001]**

> There is a tendency on the part of researchers to reach for the elegant solution when the real need is to keep developmental efforts as simple as possible. The KISS principle often gets overlooked. It seems to me that a total system approach would take as much advantage of a human operator as possible. **[Jenkins, 2001]**

> Most AUV designs are limited by power available. This comes out in the first "back of the envelope" design cycle. Those projects that then panic and go to the handbooks to choose "the best power source" rarely allocate enough effort to taming the exotic choice they came up with. There are enough problems to face, start a new AUV design with a simple power source. When it's working, then you can update the power system. **[Bradley, 2001]**

Reliability engineers know that total system reliability is a product function of the reliabilities of the critical components. As component cost is related to the reliability requirement, it becomes economically impractical to demand too high a reliability for any one component. An alternative to achieving high system reliability through high component reliability is to reduce the number of critical components. This reduction can be accomplished either through simplification, or through redundancy. Since redundancy is also expensive, simplification is preferred, as above.

However, as much as simplification is desirable, there are few real-world working examples of simple systems. From the realm of elementary particles, to the metabolism of an amoeba, to the modulation of temperature in the atmosphere, real systems are very complex, with lots of feedback and feed-forward among the components. We need a way to understand this complexity. Describing the system architecture with its information exchange requirements is one way.

There are several ways to define *simple* in the context of robotics applications. Our common conception of *simple* is something that is singular, basic or fundamental, and easy. (We also use *simple* when we mean stupid and naive.) So far, the uses in this report have suggested that a few lines of code are simple, a few system components are simple, and a limited functional capability is simple, perhaps as a consequence of the first two uses listed in this sentence. We must admit, however, that simplicity is an illusion based upon to what we are paying attention, for if something works well, no matter how internally complex it is, we can ignore it.

> A simple solution is an adequate solution. **[Hudson, 2001]**

> A robot may be of any degree of internal complexity as long as its demands on the user are simple. **[Hudson, 2001]**

Another way to look at the simplicity of a solution is to consider its compatibility with the remaining infrastructure, which is implied in the last definition by Hudson. The questions to be asked are as follows:

- Does the solution meet the requirements?
- Does it violate any of the requirements?
- Does it reduce the total costs of doing business?

A simple solution, then, makes life easier in all measures for the user. A complex solution, by contrast, is one that has the potential to increase workload and costs.

3.2.4 Other Programmatic Issues

> As a consequence of the first autonomous underwater search system (AUSS) prototype in-ocean testing, the most significant lessons were learned. These lessons resulted in major evolutionary changes to the design. Only after those design changes were implemented was system feasibility demonstrated. By that time, the technology employed in the prototype had become outdated. Sea tests, modifications or evolutions to operations and tactics, and modifications or evolutions to design and implementation became synergistic and interactive. Thus, two prototypes were required. One lesson is that the system must be designed to accommodate rapidly evolving technologies - modularity would help here. Another lesson learned is that the system such as AUSS (where the operational environment is not well understood) must be developed interactively with the user and in the operational environment as much as practical. **[Walton and Uhrich, 1995]**

The UUV industry has produced several commercial products for deep-water operation. Much of this technology is, of course, directly applicable to the VSW UUV applications. Examples are as follows:

- ✓ Commercial UUVs: deep water Maridan 600 cost from $1.5M to $2M (Maridan of Denmark); Hugin (Kongsberg Simrad/Statoil of Norway.
- ✓ Navy mine-hunting UUV: Long-Term Mine Reconnaissance System (LMRS) scheduled for initial operation in 2003.
- ✓ Royal Navy mine-hunting UUV: Marlin, developed by BAE Systems for the Defense Evaluation and Research Agency, in operational evaluation in 2001.
- ✓ Academic UUVs: Woods Hole—REMUS (~$175K); MIT—Odyssey, w/Lockheed Martin—Cetus II ($45K) ; Florida Atlantic University— Morpheus. **[Wernli, 2000]**

Table 2 lists web sites for many UUV producers **[Wernli, 2000].**

Table 2. Internet addresses of UUV producers.

URL	Vendor
www.dw-1.com	Douglas-Westwood Associates
www.maridan.dk	Maridan A/S
www.cctechnol.com	C&C Technologies
www.kongsberg-simrad.com	Kongsberg Simrad
www.racal-survey.com	Racal Survey
www.bluefinrobotics.com	Bluefin Robotics Corporation
www.fgsi.fugro.com	Fugro GeoServices Inc.
www.ise.bc.ca	International Submarine Engineering Ltd.
www.oceanscan.co.uk	Oceanscan Ltd.
www.k-marine.co.jp	Kodusai Marine Engineering Corp.
www.whoi.edu	Woods Hole Oceanographic Institute
www.soc.soton.ac.uk/autosub/	Southampton Oceanography Centre, Autosub
www.jamstec.go.jp	JAMSTEC
http://underwater.iis.u-tokyo.ac.jp/Welcome-e.html	Tokyo U., Ura Lab.
http://www.oe.fau.edu/AMS/auv.html	Florida Atlantic University AUVs
http://auvserv.mit.edu/	MIT AUV Lab

An interesting commercial website that contains much useful information on unmanned underwater vehicle technologies may be found at **[ISE]**.

An even larger list of vehicles and associated technologies specifically oriented to the MCM missions is available from **[Fletcher, 1999]**[1]. Besides a complete listing of vehicles that have been developed and/or applied to the MCM tasks, Fletcher provides useful comparisons among UUV energy sources, communication modes, methods of navigation, sensor capabilities, and mine neutralization strategies.

Most attention given to ROV and AUV MCM efforts, however, have addressed either the shallow-water or deep-water mine problems. The closer one attempts to drive the UUV to the beach, the greater the sensing, navigation, communication, and control problems become. Even in deeper water, Fletcher notes that all but one of the Fleet-deployed systems today are ROVs. The benefit of the ROV is, of course, that the human is removed from the site of the action, but human labor is not reduced, and it may actually be increased by the difficulty of task execution from a distance. Thus, the principal shortcoming of a ROV, whether on land, in the air, or in the sea, is that at least one human must continually monitor and control each ROV. Considerable information must be transferred from the ROV to the operator to make effective remote control possible. If the information is changing rapidly, as it does in the complex terrestrial environment and near the beach, or if the information is restricted, as it often is in the underwater environment, the challenges of purely teleoperated control can become task-prohibitive.

[1] Barbara Fletcher. 1999. “Worldwide Mine Countermeasure (MCM) Vehicles and Technologies.” Report submitted to the Office of Naval Intelligence. September. Contact author at SSC San Diego.

3.3 TECHNOLOGIES

RADM Kemp, PEO, Mine and Undersea Warfare, summarized the current outstanding technology issues in mine countermeasures that, in part, motivate the present project:

- ✓ Buried mined detection
- ✓ Pressure mine sweeping
- ✓ Cost
- ✓ Precise underwater navigation
- ✓ Data fusion for the common tactical picture
- ✓ VSW/SZ operations
- ✓ Stand-off neutralization **[Kemp, 2000]**

The reasons for these shortfalls in VSW/SZ MCM capability are attributable primarily to the turbulence of the water near the beach, and to the difficulties of sensing and communications in this environment. We will review these issues in the following sections.

3.3.1 Sensor Technologies

SPAWAR Systems Center, San Diego (SSC San Diego) has produced for the Office of Naval Intelligence (ONI) a survey of sensor technologies available for MCM operations **[Fletcher, 2000][2].** Sensor types covered include electro-optic, acoustic, and magnetic.

> Acoustics are very difficult in the VSW/SZ due to air bubbles, sand, and wave action. Multi-path is significant. Higher frequency acoustics provide better resolution. Most of the effort will be in signal processing due to the problems with acoustics in the VSW/SZ. **[Schempf, 2001]**

> Much has been done in the DoD community (including target classification for the shallow-water, near-shore security arena) in the field of sonar data processing. Utilize the results of this work instead of developing new sonar data processing and classification capabilities. **[Heath-Pastore, 2001]**

Chemical detectors should also be considered for mine detection and classification. Both DARPA **[DARPA01]** and ONR **[ONR01]** are programming resources that may be leveraged to explore this possibility.

3.3.2 Communications and Control Methodologies

The experts from WHOI and elsewhere with whom we interviewed were unanimous in their opinion that acoustic communications are very difficult in the VSW/SZ. Without reliable high-bandwidth communications, external control will be difficult. Some other strategies for communications were suggested, however.

[2] Barbara Fletcher. 2000. "Worldwide Mine Countermeasures (MCM) Vehicles and Technologies." Report submitted to the Office of Naval Intelligence. Contact author at SSC San Diego.

Communication in the VSW/SZ will be very difficult; acoustics are extremely noisy, and RF energy is absorbed and scattered making it next to useless. Deploy antennas for communications and navigation. **[Albus, 2001]**

Acoustics hardly ever works, especially in shallow water. **[Yoerger, 2001]**

Communications is very difficult in the underwater environment, and especially in the VSW/SZ. Using ultrasonic, the state of the art might be 19.2 baud. [**Schempf, 2001]**

Configure your project to succeed even without acoustic communications. Give the communications group a firm budget and have backups if they never deliver. **[Bradley, 2001]**

Multi-agent collaboration is also very difficult for basically the reason of poor communications. **[Schempf, 2001]**

Communications can be required either between agents or between an agent and the human operator. Between agents, distances may be quite short, and information requirements quite small. Just the opposite may exist between an agent and the human operator. One well-understood method of facilitating short-range communications is to adjust the method for the medium. As the agents are themselves immersed in the medium, if they had the ability to sense the transmission characteristics of the local medium, and had the ability to adapt their communication methods, then between-agent communications may be possible in even the most severe environments. Communications with the human operator are still disadvantaged by distance and the uncertainty of the intervening medium, but relays of communicating agents may reduce these problems. DARPA is promoting multiple UGVs to establish a flexible RF communications network **[DARPA02]**.

Computing is not an issue, but poor communications increase computing load. **[Schempf, 2001]**

Un-tethered systems require considerably more intelligence than tethered versions designed to perform similar missions. The more the autonomous capabilities of the system, the greater the range independence that is afforded. **[Walton and Uhrich, 1995]**

The iRobot Swarm control processes depend upon communications among the agents. IR links are currently used, however, trails are also under consideration. The robustness of these methods underwater is questionable, but an acoustic method of swarm control is under development at iRobot for application in the VSW/SZ **[iRobot]**.

3.3.3 Other Technology Issues

The VSW/SZ is subject to strong currents and water turbulence; vehicles will be tossed about, making station keeping very difficult. The power available to small UUVs was a concern of most developers we interviewed. Most developers indicated that navigation was going to consume lots of power, while several recommended strategies to conserve power.

> The VSW/SZ is a physically turbulent place. Just getting around will be difficult and consume lots of energy. Disk shape facilitates the crab's hydrodynamics in the SZ, Consider a vehicle the shape of the sand dollar with water jet propulsion. **[Albus, 2001]**
>
> If the agent "goes with the flow" then it needs good self-localization. **[Brooks, 2001]**
>
> Much of the power in UUVs is consumed by locomotion. Currents defeat swimming vehicles, obstacles defeat crawlers. However, a more successful strategy might combine the two. **[Schempf, 2001]**
>
> If one agent is deployed, it must have very good acceleration to operate in the VSW/SZ. **[Brooks, 2001]**

The amazing ability of Salmon to negotiate the turbulence, strong currents, and obstacles of down-rushing streams to reach spawning grounds must be admired, if not emulated.

Researchers at iRobot have tried to emulate the swimming dynamics of fish:

> The goal of the DARTs program was to develop a series of small autonomous underwater vehicles that emulate the efficiency, acceleration, and maneuverability of a fish. These biologically inspired robotic craft are equipped with a state of the art system of flexible, actuated hulls capable of producing the large burst of force needed for fish-like rapid acceleration and turning. The prototype, developed in cooperation with MIT's Department of Ocean Engineering, is roughly three feet long and consists of a series of lined actuators, a spring-wound exoskeleton, flexible lycra skin, and a rigid caudal fin. Modeled after a pike, its foil mechanism "flaps" to create vortices that produce jets of high propulsive efficiency. **[iRobot]**

Figure 4. iRobot's DARTs fish-like vehicle.

> Track drive will likely be more useful than legs. **[Albus, 2001]**

> Navigation is problematical due to poor sensing and communications, and due to the turbulence of the environment. GPS could work if one could deploy an antenna above the surface of the water. **[Albus, 2001]**

> Between an ROV and an AUV, the AUV is a niche tool: the AUV is perhaps more practical to operate at night; the AUV is more energy efficient because bright lights are not needed to help the operator navigate. **[Yoerger, 2001]**

> For an underwater application (discounting snorkeling), the UUV will be limited to battery or fuel cells. For a crawling vehicle to be able to withstand turbulence, it would have to be heavy, thus putting a larger load on power. The UGV community has found that current battery capability severely limits operational life and they are looking to fuel cells to help solve the problem. In many cases for robots under 100 lbs, the mobility and navigation power requirements limit the payload capability. If the UUV could snorkel and use a system with higher power density, that would help with the power limitations. **[Clemons, 2001]**

In some scenarios, it might be possible to have a small robotic surface platform with RF capabilities running a fossil-fuel generator, and providing power and communications to a robotic underwater vehicle to which it is coupled via an umbilical cable. The length of the umbilical cable may be minimized by coordinating the movements of the surface and sub-surface vehicles.

> Be ruthless about your hotel load. Make every effort to keep it a small fraction of the power budget. There's no excuse for a system where the computer takes 30% of the system power. **[Bradley, 2001]**

In the human, and we presume in the dolphin as well, the brain consumes approximately 25% of the body's oxygen (and thus, energy metabolism) at rest. Adaptive processes, supported by this considerable computational capability, reduce energy requirements overall.

The problem of energy reserve and conservation is not generally a significant problem for most academic developers of UGVs who either dock their vehicles at recharging stations or simply change batteries whenever necessary. Nature, however, has appreciated this problem and addressed it with three basic approaches:

- First, a large part of the sensor, motor, and central controlling apparatuses of each and every non-chlorophyll-containing organism is dedicated to the acquisition and consumption of energy, and most of the organism's active moments are so directed.
- Second, when not pursuing energy, most organisms sleep or go into suspended animation to conserve energy.
- Finally, when external energy sources are in short supply, the organism feeds upon itself. Stored carbohydrates are burned, followed by stored and structural fat, followed by structural proteins.

The top priority for a natural organism is to survive by acquiring energy, even if this takes the sacrifice of structural elements to sustain behavior in the pursuit of more energy.

Could robotic systems be similarly designed? If an energy-depleted robot is useless, then it might as well be consumed in the process of providing energy for itself so that it can continue to perform its function a little longer. To accomplish this, structural elements would have to be convertible.

Another possibility is for the robot agent to extract energy from its environment. Breaking the dependence of robots upon human operators for energy would considerably reduce the amount of human labor that is currently expended in support of the robots. It may be also necessary in order to achieve autonomously adaptive robot operations **[Blackburn, 1984]**.

4. RELEVANT UGV LESSONS LEARNED

An excellent starting point for a review and discussion of *Lessons Learned* from the unmanned ground vehicle work is a recent contribution to the *Army Science Board (ASB) Summer Study for 2000* by Jack Taylor (DUSD [S&T]) on the status and challenges associated with technologies critical to the fielding of UGVs **[Taylor, 2001] .** These contributions are primarily reproduced in the Volume on *Operations* of that study **[ASB, 2000].** Of particular interest are the several informative tables and associated text that relate UGV technologies to FCS missions and to expected availability schedules.

In its Executive Summary, the ASB concluded:

> Robotic technology will be available for the Army's planned development for either a follower or an assisted path robot with information derived from the organic ISR system. Autonomous robots were judged to be unavailable for 2006 EMD but would be available for 2015-2025 insertions. **[ASB, 2000]**

An earlier, yet still relevant, discussion of the applicability of robotic technology to military operations (primarily Army) can be found in *Robotics Workshop 2020* **[SAIC, 1997]**. The Workshop summary presented the following main points:

- ✓ A duality was noted between use of robotic systems for tasks that humans cannot or should not execute, and use to enhance human actions.
- ✓ A network of semi-autonomous mobile sensing robots of varying sizes and attributes was seen as a powerful and important application.
- ✓ Automated systems can play an increasing role in information-related tasks, including the more "qualitative" aspects of decision-making.
- ✓ Robotic systems as decoys were a favored application.
- ✓ Of the various sizes of robots discussed, "micro" robots were seen as perhaps the most important and broadly useful.
- ✓ Order-of-magnitude advances are needed in artificial intelligence and all aspects of mobility.
- ✓ Other priority robotics-related R&D pursuits include power sources, actuation, sensor fusion, and materials.
- ✓ Prioritization of R&D spending for robotics should consider which enabling technological advances must be pursued by DoD and which might be adopted or adapted from the civilian/commercial arena.
- ✓ New operational and organizational concepts will be needed to gain the maximum utility from robotic systems.
- ✓ Modularity in robotic systems was seen as highly desirable, but the associated technological difficulties may outweigh the advantages.
- ✓ There was a strong consensus to develop classes of robotic systems, probably distinguished by gross size.
- ✓ A significant degree of autonomy will be the key to robotic systems utility, but autonomy is not the same as free will.
- ✓ Participants considered the feasibility and use of "telepresence" as alternative to teleoperation.

- ✓ Development of "cyborgs" might be an innovative way to achieve covertness in robotic systems.
- ✓ Biology holds a number of potentially important inspirations and models for robotic development.
- ✓ Use of robotic systems by the military may have important implications in deterrence.
- ✓ Appropriate cultural and organizational adaptation must be considered to gain the full military use of robotic systems.
- ✓ Robotic systems must exhibit military behaviors, but they need not necessarily exhibit soldier behaviors. **[SAIC, 1997]**

4.1 OPERATIONS

We will now review *Lessons Learned* from a variety of other individuals involved in unmanned ground robotics programs, as program managers and as developers. The citations below will provide justification for the cautious predictions of the *Army Science Board Summer Study for 2000* mentioned above.

4.1.1 Lessons Relevant to a UUV Operations in VSW MCM Missions

4.1.1.1 Merits of Teleoperation

In the teleoperated vehicle (TOV) mode, the human operator supplies all of the necessary intelligence, though sometimes depending upon sensory data, usually video imagery and microphone derived audio, transmitted from the remotely located vehicle.

An in-service teleoperated vehicle used for unexploded ordnance neutralization, the RONS, provides some insights into the operational and technological issues of teleoperation.

> The Remote Ordnance Neutralization System (RONS) is strictly teleoperated, weighs 600 pounds, carries a five-degree-of-freedom manipulator arm with a 100-pound capacity. Operators drive the RONS using four video cameras, by either RF link up to 1000 meters or by fiber optic tether up to 750 meters. The vehicle can climb stairs and pass through a standard doorway. The human operator provides all of the necessary intelligence, drives and navigates the vehicle, detects targets, discriminates targets, and determines the placement of charges. The mission is to clear small areas, generally one unexploded ordnance at a time. Following placement of a charge, the vehicle is driven back to a safe place and the charge is fired. This RONS is not suitable for large mine fields. There is no requirement to operate covertly. The vehicle is powered by lead-acid batteries which can be recharged by the operator's **High Mobility Multipurpose Wheeled Vehicle (**HMMWV). **[Milcetic, 2001]**

Figure 5. Remotec's RONS teleoperated vehicle.

The conditions that accompany the RONS operation limit the applicability of its processes to MCM operations in the very shallow water, foremost of which is the need to collect and transfer back to the human operator adequate sensor information for navigation and task control. Since a human operator must drive the RONS vehicle, there is no reduction in human labor, although the human operators no doubt appreciate the stand-off range afforded.

When remotely operating the Man Portable Robotic System (MPRS) in a strict teleoperation mode, the assessment team described several challenges, including:

- ✓ limited information from on-board sensors;
- ✓ operator fatigue;
- ✓ video signal degradation;
- ✓ and poor video contrast underground. **[Laird et al., 2000]**

All the above challenges could be encountered in UUV teleoperation, along with a few more specific to the underwater environment. However, teleoperation should not be strictly dismissed as an option for the VSW MCM UUVs. While we are assured that RF and sonar communications will be severely limited in the VSW/SZ environment, a fiber-optic link from the UUV back to a control station may be practical. Such fiber-optic communications for a UUV with a range over several thousand yards was demonstrated at the Naval Ocean Systems Center (now SSC San Diego) in the early 1980s. The major difficulty with teleoperation, however, remains in providing adequate sensor information for the human operator, who naturally works best with visual input. A drawback to video based teleoperation for underwater uses is that the video camera requires reflected light from the subject, and while low-wattage chemical lights are currently used by divers for mine discrimination, projected light from a UUV is undesirable for use in covert night operation and for its power consumption.

A teleoperated vehicle, and any ROV, is simply an extension of the operator's tool set. Humans learn from childhood how best to use their hands and sense organs to operate tools in their immediate grasp. Extending those tools beyond their immediate grasp changes all the rules that they have mastered. Many children, though, already come trained in the control of ROVs, at least those that have had the opportunity to play with remotely operated or radio-

controlled cars, boats, and airplanes. The control functions for these vehicles are generally easy to learn as long as the child can view the motion of the vehicle in response to control commands. The placement of cameras on the moving parts of the ROVs to provide more proximate visual information to the remotely located human operator requires the learning of new transformations that are not common to radio-controlled toys. Not surprisingly, operators find it easier to learn the transformations when their perspective of the action is taken from a fixed location (as they have when operating a radio-controlled toy).

Retraining the operators and testing their competencies with new tools and new rules for remote manipulation must accompany the introduction of ROVs into the operational environment.

However, for an alternative opinion:

> Teleoperation is not as difficult or taxing as some would have you believe. If your designs are simple and effective, the learning curves are short. This allows operators to qualify quickly. Anything you can do to reduce the operator's workload is good, and highly dense/complex interfaces do more harm than good. **[Klarer, 2001]**

4.1.1.2 Merits of Supervisory Control

The many difficulties associated with teleoperation, combined with the current technological unfeasibility of true autonomous robotic control, have motivated researchers to try a hybrid approach to control, called *supervisory control*, or *semiautonomous* operation. In this mode, the operator provides the task planning, problem solving, and perceptual discrimination capabilities to the system, while control algorithms running on the robot provide the low-level reactive control capabilities useful for obstacle avoidance and dead-reckoning navigation.

> The general feeling among the robotics community is that teleoperation is difficult because of the manpower and communications considerations. At the same time, full autonomy is believed to be too hard to achieve. Therefore, any control scheme will have to include a capability to notify an operator when the robot has encountered difficulty or has found a target. Control algorithms will probably allow one operator to control a number of robots at one time by giving high-level orders such as search area, search pattern, way points, etc., and let the robot do the local navigation chores. **[Clemons, 2001]**

> Teleoperation is a difficult task requiring significant training, experience, and practice. Supervisory control can often support similar activities but require less operator expertise. **[Heath-Pastore, 2001]**

From a series of security robot prototypes beginning in 1980, the U.S. Navy provided technology design and integration for the development of the Mobile Detection Assessment and Response System Interior (MDARS-I) and exterior MDARS-E platforms. These platforms were designed to operate semiautonomously, following predetermined trajectories through either warehouses or supply depots, respectively, avoiding unexpected obstacles, and reporting on security events and conditions with minimal human supervision. The MDARS-I platform uses sonar, inertial navigation, and the recognition of specially prepared landmarks

to maintain its trajectory according to a given map of the interior spaces. The MDARS-E platform, shown on the right in Figure 6, uses primarily differential GPS to keep itself on track while following its surveillance route through a supply depot.

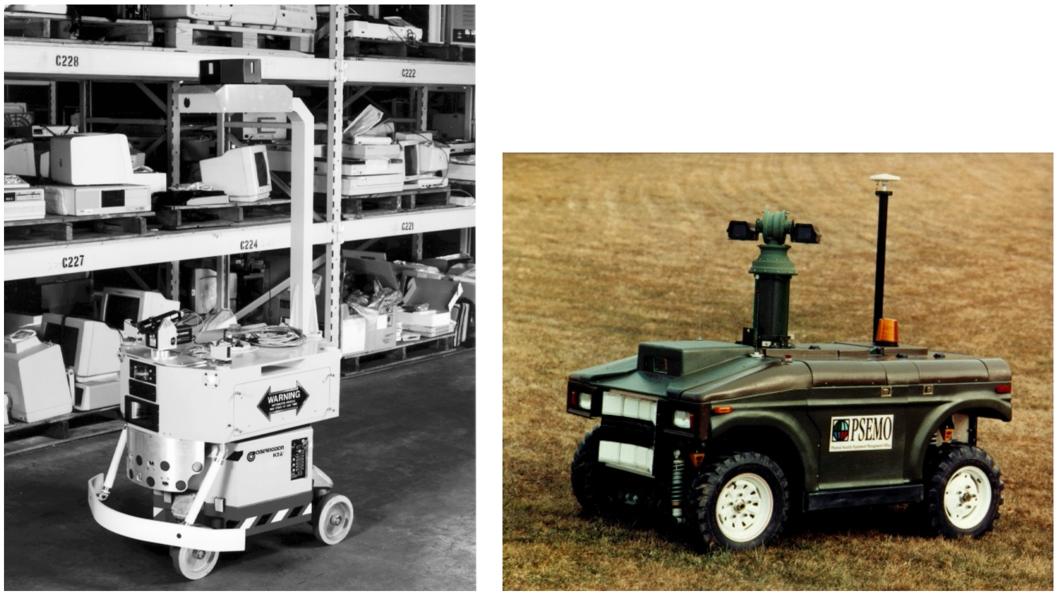

Figure 6. GDRS MDARS-I and MDARS-E platforms.

The MDARS team at SSC San Diego expected that a single operator could control a group of agents dedicated to security tasks. This expectation led to the development of the Multiple Resource Host Architecture (MRHA). The MRHA permits a single operator to command and coordinate several robotic platforms that are used in physical security and inventory and barrier assessment inside DoD warehouses and outside DoD storage sites. The automatic route following and obstacle avoidance capabilities of the employed semiautonomous robots permitted this more efficient use of human labor.

The level of supervision required by the MDARS platforms is minimized by the predictability of the operational environment. When conditions are more uncertain, more supervision is necessary to compensate for the weak perceptual and decision-making capabilities of the platforms.

> Preliminary user evaluations of the first Man Portable Robotic System (MPRS) prototype and a family of assorted Operation Control Units in tunnel exploration exercises at Ft Leonard Wood, MO have shown, however, that, under the conditions present during the experiment/demonstration, sophisticated tele-reflexive operation, even with a simple user interface, was neither required nor desired by the operators. Operators preferred to have direct and absolute control over the operation of the vehicle. **[Laird et al., 2000]**

The MPRS prototype was based on MDARS-E control technology. The amount of supervision required to ensure the safe operation of the vehicles with the current capabilities for reflexive (reactive) control in complex or uncertain environments is significant.

Figure 7. Foster-Miller platform employed as the MPRS.

The Demo III XUV vehicles also evolved from the MDARS-E design, and were employed in a RSTA scenario in an unstructured operational environment (see the next section for more on the operation of the XUV).

> Even in a supervised autonomous mode, the Demo III vehicle commanders were over taxed **[Burns et al., 2000]**.

The determination of the appropriateness of supervisory control may depend, however, upon just how busy the operators are at the time:

> Soldiers may prefer an autonomous system when under fire, but a teleoperated system when at leisure **[Dodd, 2001]**

When an even greater degree of cooperation is required among the robots, the re-addition of human operators may not be adequate. Indeed, the human operators often have coordination problems of their own.

> With Fetch II, IS Robotics [a division of iRobot] has built a test bed to address the questions that arise when multiple munitions clearing robots are employed to sweep an area. How can a lightly trained technician operate such a complex system? How can the robots cooperate with one another to perform the task most effectively? The Fetch II robots perform their tasks autonomously but with the supervision of a single operator. Behavior Based intelligence in each Fetch II enables it to navigate through real world terrain autonomously, using a relative coordinate positioning system and task-specific sensors mounted on a robust mobility platform. The Behavior Based software mediates robot-robot interference within the swarm and supports mutual cooperation among them. The operator is free to task the robots at an executive level, using a graphical map interface to define search and collection areas and mark likely or unlikely unexploded ordnance targets. The Fetch II supervisory interface supports

a range of human-robot interaction styles, from high-level re-planning to direct teleoperation for smooth operation under various contingencies. **[iRobot]**

Figure 8. iRobot's Fetch II vehicle

The plans for the deployment of robots in space face the problems of complex and uncertain environments and coordination of multiple agents assigned to the same task.
But, a high degree of supervision over robotic operations in space has been unfeasible due to the delays and other difficulties in communications.

Presently, sequences of commands are up-loaded to the space exploration robots for execution. The robot, while on the Moon, Mars, or an asteroid, executes the command sequence, if possible, and then waits for the next sequence. Serious exceptions can interrupt the sequence.

> The model of rover operations used for the Mars-Pathfinder rover, Sojourner, (and the model planned for the Mars ’03 twin rovers), is to manually generate sequences on the ground and when necessary, perform additional sequence modifications on the ground based on uploaded data. If something unexpected happens during sequence execution, such as an out-of-range sensor reading or a longer than expected traversal, the rover must be “safed” until further communication from the ground can provide a new command sequence. This procedure often causes hours of lost science time and makes it extremely difficult to take advantage of unexpected science opportunities. **[Estlin, et al., 2001]**

Clearly, a mechanism local to the robot that would generate mission-useful sequences of commands that would maintain robot safe-state parameters and deal with unexpected exceptions to the task environment could avoid the time-consuming planning, re-planning, transmitting, and reconfiguring that are now required from earth.

There is much in common between the underwater and space environments. Solutions that are effective in either environment should be seriously studied for transfer to the other.

4.1.1.3 *Lessons Learned* from the Rationale and Results for Demo III

The Demo III program employed the experimental unmanned vehicle (XUV), which was built by General Dynamics Robotics Systems (GDRS) based upon the MDARS-E platform.

> Experience with the MDARS-E platform permitted the rapid development and testing of the Demo III XUV. **[Myers, 2001]**

Demo III addressed three major areas with the objective to solve the problem of semiautonomous navigation through a complex natural terrain:

- Machine perception
- Machine intelligent control
- Man–machine interface for supervisory control.

> The issues in perception derived from the need to determine the most appropriate path for traversal. Examples of aspects of the environment that had to be detected were foliage type and density, ground slope, ground 3-D, and ground texture. The most difficult machine perception problems were the detection of below ground obstacles, and the characterization of foliage. Active millimeter wave sensors have proven useful in the latter. **[Bornstein, 2001]**
>
> The issues in intelligent control derived from the need to determine the most appropriate military (tactical) behaviors. Considerations include cover and concealment, potential ambush opportunities, and the route recon requirements. The implications of the terrain and environment must be factored into these decisions. Terrain navigation algorithms were developed upon the assumptions that cost functions could be defined as essential motivators. Cost factors included physics issues and tactical issues. Physics issues included the traversability of a depression, or of foliage, while tactical issues might be the opportunity for cover and concealment, making a depression or foliage attractive. The development and testing of these decision strategies are not yet complete. **[Bornstein, 2001]**

Figure 9. GDRS platform (XUV) employed in Demo III.

> The issues of the man–machine interface were relevant because the involvement of a human in the operation of the vehicle was always required. **[Bornstein, 2001]**
>
> The most significant lesson learned was that "you don't know what you don't know". Thus careful experimentation in the real environment is necessary. Modeling and Simulation (M&S) is useful only when you know sufficiently enough either about the operational environment or about the agent that must operate in the environment, but if there is much uncertainty about both, then you have to perform the tests in the real world, for the combined uncertainty defeats the utility or advantage of the controls possible with M&S. **[Bornstein, 2001]**
>
> The Demo III program took the approach of developing a sophisticated on-board machine intelligence, following the inspiration of Jim Albus (NIST), because of three factors: doctrine, economics, and control. Doctrine or tactics required stealth. Stealth would be lost with the fielding of random reactive agents. Economics did not permit the development schedule required to acquire, test, and retrain to a novel military application. Control was essential because of the anticipated close collaboration between semiautonomous machines and humans in the operational environment, and could not be guaranteed with random reactive machines. **[Bornstein, 2001]**
>
> The focus on the RSTA mission was designed to encourage user input. The objective of the Demo III program, however, was not to develop a scout vehicle per se, but to develop semiautonomous navigation capability in a natural terrain. Thus, neither was ATR a high priority investment but did receive attention because of the RSTA mission scenario. **[Bornstein, 2001]**
>
> Communications were addressed using available military equipment at the brigade level. The limited bandwidth afforded by the available radios required attention to greater on-board processing capability. **[Bornstein, 2001]**

User feedback on the capabilities of the Demo III XUV has been extremely informative, not only for the utility of the state of the implementation of the technology, but also on the match between user expectations and robot functionality. Following is a sample from the Battle Lab Experimentation Final Report (BLEFR) for the Experimental Unmanned Vehicle (XUV) Demonstration III ALPHA, May 2000.

> In this experiment, XUVs operated from one to two kilometers in advance of the manned HMMWV to which they were assigned. The user interface, the Operational Control Unit (OCU), is a stand-alone computer that allowed the HMMWV commander to control the two XUVs assigned to him. The communication system for these XUVs was the Near Term Digital Radio (NTDR) system. **[Burns et al., 2000]**
>
> The Automatic Target Recognition (ATR) had a very high false-alarm rate and had to be turned off to prevent inundating the operators with (false) target reports. Target detection was limited to those manually panoramic (near-real time) images by the OCU operator. **[Burns et al., 2000]**

The XUV's limited obstacle avoidance ability required high vigilance and close following by manned safety vehicles; numerous emergency stops (e-stops) of the XUVs interrupted the natural flow and development of scout missions and the experiment. **[Burns et al., 2000]**

Continually evolving diagnostic procedures resulted from different vehicle software configurations and hindered the collection of consistent data over the entire trial set. **[Burns et al., 2000]**

XUVs were assigned 36 route-reconnaissance missions. On six occasions, the XUVs failed to respond to the mission execution message sent by the OCU. These six failures are attributed to failure in radio communication between the OCU and the XUVs, not to the OCU. **[Burns et al., 2000]**

Conclusions from the experiment:

- ✓ The XUV had no capability to avoid negative obstacles.
- ✓ The XUVs demonstrated a limited capability to avoid positive obstacles. The Demo III ALPHA XUV could not detect enemy vehicles. **[Burns et al., 2000]**

General Recommendations from experience with the operational control unit (OCU):

- ✓ Add motion video as opposed to still imagery.
- ✓ Add necessary sensors and pass information to the OCU to let the OCU operator know the location of robots and what the robots are viewing.
- ✓ Provide default RSTA function whenever the XUV doesn't move or gets stuck.
- ✓ Provide an indicator on the OCU screen of the XUV inoperabililty.
- ✓ Provide grid lines on OCU graphics.
- ✓ Provide "Vehicle Health Status" function to the OCU interface.
- ✓ Provide depth perception, tilt, and slant of the robots to the operators. **[Burns et al., 2000]**

While most of these comments appear to be in the category of deficiencies, and do not represent the successful accomplishments of the Demo III ALPHA experiment, problems yet to be overcome in a semiautonomous (semiautomatic) land vehicle are certainly obvious. Later in this report, we will introduce comments and *Lessons Learned* from the technical side of this particular experiment. (Demo III BRAVO results from the September 2000 experiment were not available during the writing of the present report in April 2001.

The DARPA/Army Demo III program is a bold attempt to provide navigational capability to an unmanned vehicle. The MDARS-E program, using similar technologies, is one of the few other DoD robotics efforts to attempt semiautonomous (semiautomatic) navigation. At the Force Protection Equipment Demonstration (FPED III) in May 2001, at Quantico, Virginia, the MDARS-E vehicle was the only UGV present and operating that did not depend on strict remote human operator control for operation. Other UGVs at the demonstration included those manufactured by Foster–Miller, I-Robot, MESA Associates, and Romotec.

These last robots were all operated by remote control (TOV/ROV) through either a fiber-optic or radio link. Practical examples of semiautonomous vehicles are rare.

4.1.1.4 Merits of a Complex On-board Intelligence

Given the operational difficulties of controlling a ROV in any complex environment, we need to consider the alternatives. Some of the alternatives that UGV developers have suggested include the addition of automatic control processes that may preempt operator actions, or kick-in when the operator fails to act appropriately, and automatic processes that generally control the UGV unless preempted by the operator.

These alternatives scale to the degree that the UGV contains sufficient sensor and computational resources to make navigation and task decisions independently of a human operator. To make independent decisions, whether good ones or bad ones, the onboard intelligence must receive information that would ordinarily be available to the human operator. This list includes state information on the vehicle, a variety of environmental state information, and some elements from the tactical picture. In addition, the vehicle has to have the means by which to act appropriately upon that information; otherwise, we cannot say that a decision has actually been made.

What type of intelligence is required onboard any robotic agent to integrate the available information and execute some appropriate response?

> Different approaches to robotics control: knowledge-based vs. behaviorist; deliberative vs. reactive **[Albus, 2001]**

Very briefly, we will try to contrast these approaches. Knowledge-based and deliberative approaches share the infusions of abstract information from human experiences, which are then saved in searchable data structures. As the robot's circumstances evolve, the control process attempts to keep up by recalling, or reconstructing from the available data, a sequence of appropriate responses. The knowledge-based/deliberative approach takes its inspiration from the cognitive psychology literature. Expert Systems are one form of knowledge-based artificial intelligence, and have made great chess players. The chess game is a closed environment, and the rules are adhered to during the game, making it possible for optimal or near optimal plays to be determined. Expert Systems break down in less constrained environments.

The behaviorist or reactive approach encodes somewhat independent low-level responses to specific events that generalize to a great variety of circumstances. The robot functions by reacting with approach or avoidance responses to classes of environmental events and stimuli. The most well-know proponent of the behaviorist/reactive approach is probably Rodney Brooks at MIT. The behaviorist/reactive approach takes its inspiration from the neuroethology literature. Neuroethology has excelled most in the study of bugs, fish, and frogs, species that do not appear to depend much upon contemplation. And while these species survive well in their native habitats, rapid changes to their local environments can wipe then out. We should expect reactive robots to be similarly vulnerable.

Neither the knowledge-based nor the behavior-based approaches adequately represent the biological mechanisms of intelligence from which they derive their inspiration. Some

essential components of the mechanisms have always been missing from both. We suggest that the critical and fundamental elements that have been missed are those that define autonomy in the biological system, whether that system was a bug, a frog, or a prince.

The limitations of architectures of automatic processes have become apparent to the most notable proponents of the behaviorist approach, who are working toward remedies.

> IS Robotics' Self-Adaptive Software (SAFER) project was developed to make existing behavioral control systems more flexible and adaptive. Current systems are not efficiently structured, and are therefore difficult to program, forcing software engineers to rewrite the same functions for different robots and debug code by trial and error. … Behavioral control is a decentralized approach to the architecture of robotic control systems. In these systems, control is distributed among a number of asynchronous behavior modules organized in a subsumption architecture, in which each module is capable of operating without input from higher layers. … Although these systems deliver all of the advantages of behavioral control, they do not provide high-level structure or system feedback. … By adding structure to multiple behaviors, incorporating performance criterion into the behaviors, and adding facilities to monitor the performance of behaviors, IS Robotics will establish a framework for adapting robot behaviors to reflect mission goals and their success. **[iRobot]**

A greater discussion of the differences between the knowledge-based and behaviorist approaches goes beyond the objectives of the present exposition, but the lesson is that each of those approaches has been explored with varying degrees of situational success. Neither has proven so far to be generally applicable.

A second question deals with the amount of intelligence that is required.

> What makes more sense is better intelligence in a few UUVs: Go with a rich world model. Map the environment. Carry templates of the expected mine types. Planning is easier with a rich model, and planning must be continuous. **[Albus, 2001**]

Albus is indicating that even if the state information is provided, all of the equipment needed to operate are working, and the computational resources are adequate to the processing load, intelligent results cannot be expected unless the decisions made are based upon prior experiences. By extension, the greater the number of combinations of state variables that could occur and that could be germane, and the greater the number of responses that are subject to success or failure, the larger the base of experience that must be available for processing.

While there is no universal agreement on the answers to the questions of the quality and of the quantity of the intelligence required, there is general optimism that the tools needed to answer these questions are improving rapidly.

> Computing power continues to increase, but at present falls far short of even the computational power of a rat (~50 BIPS). For another rough estimate, the computational power of the human brain is 100 TIPS (100 trillion instructions per second). **[Moravec, 2000]**

An objective of the VSW MCM UUV program is to reduce the need for human divers and marine mammals to come into direct contact with mines. Humans and dolphins, however, are examples of the most intelligent species on the planet. Due to the difficult operating conditions of the mission, considerable onboard intelligence supporting the mission functions may be required. Dr. Moravec's analogy may provide a rough estimate of the feasibility of this objective. Moravec yet continues …

> The incremental growth of computer power suggests an incremental approach to developing robot intelligence, probably an accelerated parallel to the evolution of biological intelligence that's its model. Unlike other approaches, this path demands no great theories or insights (helpful though they can be): natural intelligence evolved in small steps through a chain of viable organisms, artificial intelligence can do the same. Nature performed evolutionary experiments at an approximately steady rate, even when evolved traits such as brain complexity grew exponentially. Similarly, a steady engineering effort should be able to support exponentially growing robot complexity (especially as ever more of the design search is delegated to increasingly powerful machines). The journey will be much easier the second time around: we have a guide, with directions and distances, in the history of vertebrate nervous systems. **[Moravec, 2000]**

There are two critical factors in Moravec's hypothesis. First, there must be a continuing orders-of-magnitude increase in the computing power available for our artificial intelligent systems. Second, there must be an increasing viability of the artificial intelligent systems that we produce with that computing power. The evidence is that we are doing pretty well on the first factor, but how are we doing on the second?

Moravec's choice of the word *viability* is quite significant. It implies *survivability* or success against adversity. We must ask if the artificial intelligent systems that we produce are successful in this way. The jury, composed of all field tests of robotic systems, has demonstrated that they cannot survive on their own. They must be guided, supervised, protected, and nurtured. We have no autonomous robots.

We should consider Moravec's second factor carefully. If we should expect that viability will improve as a function only of the numbers of instructions per second that are available to the computing plant, without the guiding theories or insights into the evolutionary mechanisms of intelligence, then we must be prepared to suffer many evolutionary dead ends. A predecessor has noted that a pile of bricks, no matter how big, will not constitute a city. Some organizing architecture must be applied. Do we now have the right architecture in our designs of UGVs? Clearly we have not implemented the architecture used by nature in the design of the sensor and information-processing components of the human and dolphin in any of the major UGV systems. We have not even implemented the architecture used by nature in the design of a cockroach, for the cockroach survives even under our very determined efforts to eradicate it.

There is a most important lesson here. If humans remain in the information-processing loop, or if humans must remain in the system operational loop, then the inadequacies of the artificial intelligence designs will be masked by the presence and capabilities of man and the evolution of even more complex designs will be based on a "house of cards." For an artificial

intelligent system to be viable, it must work unaided by man. Indeed, it should attempt to survive under human efforts to defeat it.

> A useful approach might be evolutionary computing. **[Swinson, 2001]**

Thus, we should start small, very small, and restrain our ambitions until we have created a device that can get along in a very limited environment without us. Next, we should add capability, not to satisfy our fancies about what we would like the device to do, but rather for the device to meet and survive one new challenge in its environment. Only after that one new challenge has been successfully met should we introduce a new challenge, and explore the necessary intelligent mechanisms to survive it as well. This process is evolutionary computing.

For robots to be useful, they must enjoy survival-promoting autonomy and sufficient intelligence so as not place additional burdens upon the operators. Some of the requirements put forth by users and developers suggest the following:

- ✓ A vehicle must take care of itself:
- ✓ The vehicle must auto right and exhibit other auto escape and recovery modes.
- ✓ The vehicle must recharge quickly.
- ✓ The vehicle must automatically reacquire lost communications.
- ✓ The vehicle must discourage abuse and curious or careless handling.
- ✓ The vehicle must know where it is or geo-localize itself.
- ✓ The vehicle must negotiate obstacles. **[Blitch, 2001]**

> Homing behavior would be useful. **[Dodd, 2001]**

Even the above list contains several rather sophisticated and advanced capabilities needed to meet rather ordinary tactical challenges. The fundamental objective in the above list, though, is that the operating vehicle must reduce the workload on its operators or human collaborators. A related principle involved is that to improve the probability of mission success, the vehicle must continue to operate under adverse conditions even when there are no human operators or collaborators around to assist. We should not expect to accomplish this as an afterthought. Instead, it must be fundamental to the design.

In the following, Schwartz agrees with the assessment of the problem, but has a different perspective on evolution.

> I think of evolution as, first and foremost, a matter of growing understanding and experience on the part of researchers and operators. **[Schwartz, 2001]**
>
> Tactical applications of unmanned vehicles in unstructured environments are tough and the technology for highly autonomous UGVs (UUVs?) is not here yet. Demo III probably represents the state of the art in autonomous UGV mobility. There have been a number of false starts and I'm not sure they are at an end. **[Schwartz, 2001]**
>
> Ideally, one would like an evolutionary path that leads gradually from manned to unmanned operation, but I usually am unsure how to come up with such a path. Evolution should mean a gradual shift in the division of labor from operator to robots.

> This requires that a flexible division of labor be built into the design that allows adjustment of operating procedures based on experience (as well as on immediate operating conditions). **[Schwartz, 2001]**
>
> Another possible example of evolution would be to try to overwhelm the problem with sensors and processing (damn the expense) in order to achieve a very high level of performance. Then start to back down in some areas (while improving in other areas) and see whether this can be done so that performance degrades only slightly, but cost declines dramatically. **[Schwartz, 2001]**
>
> Somewhat related to the last thought is the idea that "single thread" designs are guaranteed to be fragile. A competent unmanned system to perform complex tasks autonomously is going to require a design that embodies fusion of multiple approaches. **[Schwartz, 2001]**
>
> The evolution of tactical robotic systems must involve the operators. Thus we should start with a manned system, and add a coupled robotic component. The robotic component must permit improvements in the survivability and/or mission effectiveness of the manned system. Doing so will demonstrate a value in excess of a threshold defined by cost and cultural factors. In order for the robotic component to permit improvements in survivability and/or mission effectiveness, the robot must have in its repertoire a number of behaviors or functions with which the operators can experiment as they adapt their tactical operations. The operators may include in their experiments varying degrees of coupling between the manned and unmanned elements. In this way the operational aspects of the system of manned and unmanned elements may evolve. This process says nothing about how to supply the repertoire of robot behaviors, but it does offer a methodology to select those behaviors that are useful. **[Schwartz, 2001]**

We are returned to the problem of developing or evolving the repertoire of robot behaviors.

The prevailing concept of the evolution of robot technology and operational capabilities from TOV to AGV is reminiscent of the ontogeny of man from infant, to child, to adolescent, to mature and independent adult, in that in human development a shift in performance responsibility gradually occurs from the parent to the child as the child matures. The critical difference here, however, between a human infant and a ROV is that the infant already contains all the elements necessary for autonomous behavior, including the ability to ask for help when help is needed. The product is essentially complete by the age of 2 years, even though it is generally useless to all except itself. The ROV, on the other hand, has none of the essential elements for autonomy. No amount of experience will help it mature. The initial design of the ROV is all wrong if competent autonomy is what we eventually need.

We face a dilemma. The dilemma is that we need to incorporate robots into our operational environment in such a way that significant realizable benefits result, yet we can neither afford to pursue, nor are likely to achieve, the development of complex behaviors without first establishing a foundation of rather trivial autonomous processes.

4.1.1.5 Why it is Hard to Move from Teleoperation to Vehicle Autonomy

We are arguing that the difficulty in providing for autonomous capacity in robotics is in the design concept for the vehicles. That concept is simply that the system must meet the needs of human operators and auditors. These needs so strongly influence the design that the operator or auditor is considered a virtual passenger of the robot. For example, the Demo II vehicle was a modified HMMWV, originally designed to convey and protect human passengers. The Demo III vehicle is an extension of this same concept. Principally, it is designed not to roll over (humans generally do not like to roll over), and to convey sensor packages that look out upon the world for the benefit of human observers as if they were riding along in the vehicle. The Demo III vehicle concept is a mobile video camera.

The current wisdom for fielding successful robotic systems is to make them warfighter friendly, or to put it differently, to make the system architecture warfighter-oriented.

While this wisdom is relevant to the degree that the human operator will be involved in the control of the UGV, as when the UGV is a ROV, or participate directly in the task with the UGV, it may impose unnecessary constraints upon the UGV design and operation.

To address the problem stated above, however, we might rephrase the wisdom to: *Do not build an architecture around the concept of the human operator. Make the architecture task-oriented.* Then, if part of the robot's task is to acquire information while avoiding bullets and other obstacles, and to relay that information back to a human subscriber, the robot's architecture should represent design priorities that are directly related to its task priorities. It first must (1) get around, (2) survive by avoiding obstacles of all probable types, (3) acquire information, and (4) relay that information.

The UAV designs appear to satisfy the above requirements in the proper order, for they fly first, avoiding most obstacles (there are, after all, few in the air), and acquire and transmit information third and fourth. The small tractor drive vehicle, the Foster–Miller Lemming, as used by MPRS, also approaches this design philosophy. The Lemming vehicle has a very low profile (about 13 inches), can drive right-side up or up-side down for as long as its batteries last (about 3 hours). If provided with GPS-based way-point navigation and obstacle escape algorithms at least as sophisticated as those of a beetle, the Lemming should be able to traverse unaided a few thousand yards of terrain, making a net forward progress at about 1 foot per second.

It is hard to move from teleoperation to full robot autonomy because it is hard to develop the perceptual and decision-making abilities of man in a computer program, and because we have not understood how to develop the perceptual and decision making abilities of even a cockroach, and because the autonomy of man did not evolve from the teleoperation of a cockroach, but rather it developed from the autonomy of a cockroach.

If we do not require the robot to behave (operate) like a human operator, but instead find uses for the behavioral capacities of much simpler species, then the achievement of autonomy at that level might be a little easier.

Humans have found uses for simple biological systems. For example, yeasts are added to grains and fruits to transform carbohydrates into alcohol and CO2. The value of bee-keeping

has long been recognized, and more recently, predatory insects are released into orchards to control other insect pests. Can we come up with similar useful applications in the context of VSW/SZ mine countermeasures, and can we develop even the simplest forms of autonomy in robotic systems to address those applications?

At first, we must be satisfied with solving—providing the capabilities for—very simple tasks. Then we may add little by little to the task difficulty, achieving solutions at each point, all the while evolving the computational complexity. At some point, we may find that the solutions no longer support a robustly survivable system. It would be appropriate at that point to end further development of that architecture and try some other promising designs.

We have been using the term *semiautonomous* to refer to a system that contains low-level automatic functions in combination with teleoperation for direction and veto control by an operator. This term, *semiautonomous*, is probably a misnomer, as there can be no autonomy in combination with teleoperation, and because the low-level automatic functions do not define an autonomous capability. Automatic functions, often implemented in behavioral or reactive processes, require useful criteria for shaping the degree and direction of the responses to achieve autonomy. The most useful criteria from the point of view of the agent is the preservation of energy reserves and the integrity of the whole (see Section 4.3.5.6 for definitions of autonomy in a natural as well as an artificial context). We should, for accuracy, use instead the term *semiautomatic*.

This differentiation of automatic from autonomous processes is not intended to minimize the importance of automatic processes. The widespread acceptance of the automation provided by industrial robots has adequately proven its utility. There is a very reasonable, and now demonstrable expectation that similar automatic processes can be implemented in mobile robots that are properly supervised. There is then a navigable path between teleoperation and automatic robots, through semiautomatic designs, but this path will not take us to autonomy if that is our objective; and we will surely find that unaided automatic robots will not meet our operational objectives.

4.1.1.6 Tactical Utility of Some Elementary Tasks

At this point in our commentary, we may need to list, as examples, some elementary tasks that might enable autonomy in very simple agents. We should also assess the potential of these tasks for tactical use.

Example #1: As the criterion for autonomy is survival, and the transformation of energy is evidence of survival, an autonomous agent should be able to manage its acquisition and use of energy. A source of energy that is generally available to UGVs during the daytime is sunlight. We have the technology to capture solar energy and transform it to electromotive power. A small UGV, if provided with a bank of photovoltaic cells, high-density storage batteries, some actuators, levers, sensors, and control algorithms, could spend its daylight hours seeking out the best exposures to the available sunlight. Jet Propulsion Laboratory's (JPL) Nanorover is an appropriate vehicle for this application **[JPL]**. The vehicle would require sensors for its energy reserves, charge and discharge rates, and for the intensity of sunlight falling on its photovoltaic cells. The control algorithm would have to decide between energy expenditure involved in its search strategies, and passive collection of solar energy

under the given circumstances. The tactical utility of such an agent could depend upon the importance of having an agent that optimizes the recharging of its batteries.

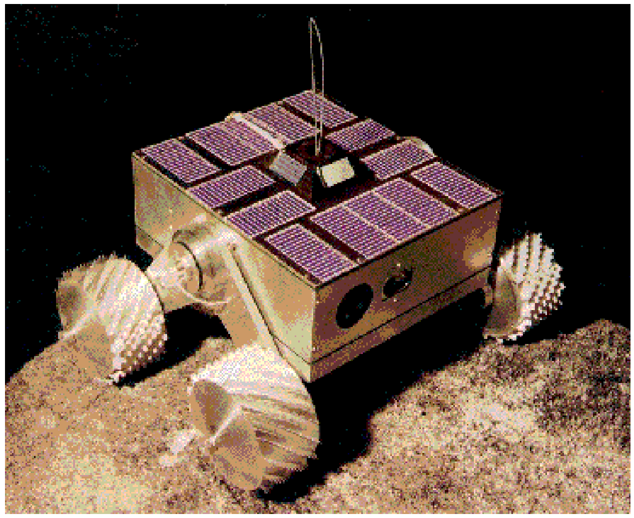

Figure 10. JPL solar-powered Nanorover.

(Image was provide through the courtesy of the Jet Propulsion Laboratory
California Institute of Technology, Pasadena, California)

Example #2: If it was tactically useful to distribute agents of a type described in the first example over a large territory with equal separation, then the agents may require a proximity sensor that gives separation information. One method to accomplish this is to have each agent broadcast a signal that is offensive to all other agents. That is, each agent attempts to move away from all other agents whose broadcast signals it detects. As the separation distance increases, the strength of the detected signal also decreases and the motivation to move away from the signal source decreases. Comparisons of signal strength from different directions may permit the center of a swarm to remain in place while the peripheral elements expand the area of occupation. This simple mechanism should cause all agents to flee from all other agents and to maintain a fairly uniform standoff distance until the signal strength falls below some critical threshold for motivation. The definition of uniform would be based upon signal strength, however, rather than upon physical geographic locations. An interesting interaction of this control algorithm with the control algorithm of *Example #1* could permit the agents to congregate in a location of high light intensity until their batteries were sufficiently charged to increase their broadcast signal strength. Nonlinear bifurcation functions for these control algorithms could prevent fixations at equilibrium points.

Example #3: If it was tactically useful to have the distributed agents collect local environmental information and convey that information back to a human auditor, the broadcast signal of *Example #2* could be used as a carrier of local information. The distribution algorithms of *Example #2* could produce a network of agents that maintained themselves just within hailing distances of one from another (including the human auditor if an agent was physically attached to the auditor at the edge of the pack), if the signal strength requirement for communication was lower than the signal strength threshold for separation. Ultra-wideband (UWB) radio is an ideal technology for this application because it consumes little power, and the timing of its pulses can be used to compute relative source locations.

Example #4: If it was tactically useful to maintain the network under conditions of the periodic loss of agents, then the thresholds for separation of *Example #2* could be modulated by the number of UWB radio broadcasts received. As agents were removed from the network (either through battlefield attrition or loss of power), the number of broadcasts received by other agents would decrease, and the separation thresholds could be increased, bringing them closer together and thus filling in the gaps. As agents came back online following their auto-recharging, the network could once again expand.

4.1.1.7 Compatibility with the Operational Infrastructure

> Must understand the operational constraints. The new technology must fit in with the operational infrastructure. **[Toscano, 2001]**

Conversely, the availability of teleoperated, mixed-mode (semiautomatic), and fully autonomous robots in the battlefield will likely change the operational environment.

4.1.2 Lessons Relevant to Target Localization and Mapping Techniques

The UGV community has been involved in mapping techniques from their inception. The purpose of mapping, however, was not necessarily to locate specific targets for later acquisition by some other agent, as is the primary objective in current MCM operations, but rather to facilitate the navigation of the UGV through the environment from and to various locations. The map was used to plan unobstructed paths. In relatively structured environments, such as the interiors of buildings that walls and doorways define, mapping errors are minimized by the short distances from the identified reference points. Short-range sonar was the sensor chosen for mapping.

The difficulties with the addition of target identification and mapping to the data structures developed for navigation would be associated primarily with perceptual problems in the discrimination of the targets. As sonar did not contain sufficient information for target discrimination, other sensor modalities such as vision and barcode and RF tag reading were used. Only vision, though, was useful for non-cooperating targets.

Mapping with a UGV in the exterior environment posed problems more similar to the underwater environment. Walls and doorways were too few and far apart for sonar to be used to map them and to provide real-time geographical location information for navigation. The exterior MDARS robot uses primarily differential GPS to map and to keep its position registered when negotiating the open out-of-doors spaces. Of course, without surface-penetrating antennas, GPS would not benefit an underwater vehicle.

Another simplification generally permitted in UGV mapping projects is that the environment is two-dimensional. That is, the mapping algorithm assumes that any object present on the ground plane extends vertically into the third dimension, and thus represents an impenetrable obstacle, but the vertical dimension is otherwise irrelevant, as the vehicle neither hops nor flies. Since the vehicle's motion is confined to two dimensions, such a representation of the environment is adequate. This simplification may or may not be useful in the VSW/SZ.

Generally, the UGV mapping approaches required stable and recognizable reference points. GPS provided reference points for the external environment. Rigid walls provided reference points for the interior environment. If the GPS information changed, or if the walls moved, neither could have permitted accurate mapping, unless the changes were also understood and predictable.

> Most academic robotics examples today are too constrained to be applicable in the real world. **[Thrun, 2001]**

The academic robotics examples are also in many cases the most advanced. What about the algorithms must be changed to reduce the constraints? If the academic researchers could answer this question, would they have already done so?

4.1.3 Lessons Relevant to Operational Logistics and Supportability Issues

> It is desirable to have maintainability at the user level **[Milcetic, 2001]**.

> Develop a system with as many line replaceable units (LRUs) as possible. The more component or modules that you can allow the soldier/Marine to identify problems with and replace in the field the better off you will be. Establish a well defined, easy to follow logistics trail. Simplify. We typically use contractor logistics support. **[Anderson, 2001]**

> Logistic support of the RON is provided by the contractor, who maintains the depot and delivers supplies to the field. **[Milcetic, 2001]**

The viability of the contractor should be a consideration for long-term logistics support. Several robotics efforts in academia and DoD have been negatively impacted by the inability of the principal supplier to continue in business, while the small product market precludes the availability of alternative suppliers.

4.1.4 Lessons Relevant to Concepts of Deployment/Recovery

> Georgia Tech generally deploys and recovers robots under very controlled circumstances, so there's not much to offer here for tactical insights. The TMR program has advocated "marsupial" deployment of smaller unmanned systems from larger ones, and we have a limited capability to use an unmanned Hummer as a delivery vehicle. Clearly, there is some applicability of this technique to UUVs. A swarm of small UUVs (maybe SZ MCM crawlers) may be completely incapable of reaching a destination across open seas, but could be easily delivered by a larger free-swimming UUV of more traditional design. **[Collins, 2001]**

4.1.5 Other Operational

> There is a need for a Joint Architecture. There is too much isolation between the UGV, UUV/USV and UAV communities. Strictly from a UGV standpoint, the JAUGS initiative is a step in the right direction. This is a topic which was discussed at a recent seminar hosted by the Innovation & Transformation Center of the Joint

> Experimentation Directorate, and they may be able to provide some of the briefing materials that came out of our discussions. **[Collins, 2001]**

See Section 4.3.5.1 for more on JAUGS.

Dr. Steven Metz's Strategic Studies Institute paper is a most interesting, if not highly speculative, discussion of the applications of robotics in military operations in the first quarter of the 21st Century. **[Metz, 2000].** Unfortunately, Dr. Metz provides no insights into the relative merits of the different technological approaches that might be taken to achieve the required capabilities for his applications.

4.2 PROGRAMMATICS

4.2.1 Lessons Relevant to Acquisition Strategies

> Useful to have "best-effort" contracts for a fixed dollar amount (R&D). **[Toscano, 2001]**

> Make sure there is a commercial base that can take advantage of competition. **[Toscano, 2001]**

> Viable commercial applications will stimulate robot development. **[Moravec, 2000]**

The Program Office may fruitfully cooperate with industries or other agencies that have a stake in the exploitation of UUVs in VSW. Examples may be fishing, and environmental preservation or restoration (e.g., following oil spills).

One essential question of the acquisition strategy (for the Remote Ordinance Neutralization System [RONS], see Section 4.1.1.1) appears to concern the degree of control over the developmental process that should be maintained by the Program Office, versus the degree of control that should be turned over to a Prime or Integration Contractor. Overall costs to delivery could be lower in the latter case, but in an area where either the technology base or the operational doctrine are rapidly changing, the former might be more appropriate.

> The acquisition strategy included R&D and production phases to the same contractor. This permitted rapid transition to MS III productions and early fielding of the product. This was made possible by an existing commercial capability that nearly met the military requirements. The difficulty with the strategy became apparent when product improvements were required. A new contract had to be written to perform Planned Product Improvements (PPI). New requirements are managed by an IPT that negotiates risks for technology, schedule, and cost. A possible solution to the dilemma of anticipating PPIs when the details are unknown, and yet using the original R&D & production contract, might be to write R&D delivery orders. **[Milcetic, 2001]**

> The High Altitude Endurance Unmanned Aerial Vehicle Program required unanticipated software development and unexpectedly complex integration tasks causing schedule slips and cutbacks in scope. The contractor, while relieved of

traditional government oversight, did not develop and implement necessary management controls of its own. **[Drezner et al., 1999]**

All programs that attempt to provide for useful semiautomatic or autonomous behavior in an unmanned system will face these complexity issues. An acquisition strategy that provides too much autonomy to the contractor, no matter how experienced or competent, risks unpleasant surprises as a consequence of the contractor's struggles with the unexpected.

4.2.2 Lessons Relevant to Test and Evaluation

When developing performance specifications, be clear and concise on the performance requirements without telling the contractor how to build the system. Keep the number of people on your integrated process team that is developing performance specifications to the lowest number possible. Too many will just clog up the process. Filter the performance specifications through the requirements developer to make sure that your interpretation of the performance and theirs is the same. **[Anderson, 2001]**

Affordability must be a key performance parameter. **[Toscano, 2001]**

How to identify Key Performance Parameters? Create a list, vote on importance, assign weights, take the top few on the list. Make sure that they are testable. Examples: minimal time on target, portability, survivability given specific threats. **[Milcetic, 2001]**

The man-machine interface must be tested in a high-stress condition. **[Dodd, 2001]**

It is difficult to quantify the performance of a real robot in a mission of any significant complexity. There are too many parameters to vary to allow any systematic investigation of the possibilities, especially since actual runs can take a while. It is reasonable, though, to task human test subjects with robot missions and allow them to “specify” (essentially to construct the robot program) and test these missions in simulation. That is the typical nature of our usability studies mentioned earlier. In such studies, the performance parameters are mission success, time to specify (construct) mission, number of mouse-clicks, number of “do-overs”, debriefing comments, etc. **[Collins, 2001]**

4.2.3 Lessons Relevant to System Definition

Requirements might be divided up among several system solutions, each taking on a piece of the problem. **[Toscano, 2001]**

There is a tendency to focus on technology that enhances the performance of the unmanned vehicle(s) as opposed to focusing on enhancing the performance of the system that includes not only the unmanned vehicles but also the human operators and the communication. The division of labor between the robots and the operators and maximizing the span of control of the operators are critical issues. To the maximum feasible extent, robots should be able to ask for help from the operator. **[Schwartz, 2001]**

Don’t go for the "Swiss Army Knife" solution. One robot need not do it all. Several more specialized but cheaper robots might serve as well, if not better. Deploy the specialized solutions as intelligence and the situation dictate. **[Schempf, 2001]**

Sensing will also be very difficult. Low-frequency acoustics may work with multiple vehicles creating a sensor array, but this demands good communications, which are unlikely. **[Albus, 2001]**

Modular designs permit upgradability by parts. **[Heath-Pastore, 2001]**

We [at SANDIA] have had success making our software and hardware somewhat modular, and have managed to 'standardize' on a few configurations but in some ways that limits what you can accomplish. **[Klarer, 2001]**

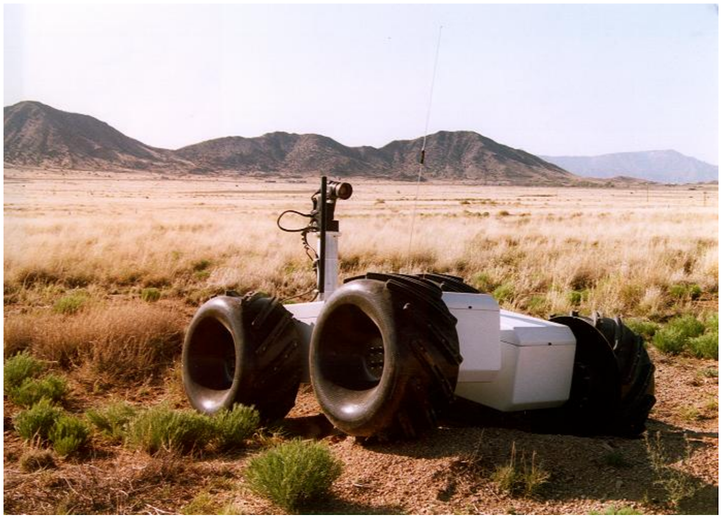

Figure 11. SANDIA Hagar vehicle using modular technology.

4.2.4 Lessons Relevant to Other Programmatic Issues

4.2.4.1 *Lessons Learned* from Early Navy Robotics Programs

Bart Everett, in a 1985 Naval Sea Systems Command (NAVSEA) technical report, identified causes for difficulties in many early Navy robotics programs:

- ✓ Poor communication and feedback between all concerned parties, particularly with users.
- ✓ Inadequate understanding of required operational capabilities, coupled with a lack of appreciation for the technology deficiencies.
- ✓ No workable long-term robotics plan.
- ✓ No baseline assessment of technology capabilities and deficiencies.
- ✓ Failure by project managers in the initial planning stages to possess a working knowledge of the technology and actively use the [available] resources.

- ✓ Inadequate 6.1 and 6.2 efforts prior to initiating 6.3 level development.
- ✓ Failure to meet design goals due to the existence of technology voids unidentified early in the process. **[Everett, 1985]**

Elaborating upon the above list, Everett continued:

> The challenge is to keep existing projects from overreaching, while building up a well developed robotic technology baseline. Timely and appropriate steps must be taken to ensure that available robotic technology is employed … **[Everett, 1985]**
>
> …the measure of effectiveness for specific applications must be determined. Development and use of appropriate cost models, understanding of system needs, and the requirement for compatibility and standardization are all important…**[Everett, 1985]**
>
> …program activity [must be extended] into such areas as intermediate and depot level repair [to control life cycle costs]. **[Everett, 1985]**

Additional concerns include the impact on training, manning levels, operational concept validation, and mission readiness.

4.2.4.2 Lessons Motivating the MDARS Program

Everett, in a later look at the historical short-comings of some predecessor projects, produced the following list as part of a report on the acquisition strategy for the Mobile Detection, Assessment, and Response System (MDARS) project.

- ✓ Lack of a bona fide application and validated payback.
- ✓ Ignorance on the part of the project manager and/or developing organization as to what the user really wanted.
- ✓ Lack of awareness in the minds of the user as to what the near-term technology could and could not support.
- ✓ Overlooked or under-estimated systems integration efforts.
- ✓ Constantly changing goals and objectives, sometimes as a result of turnover at the program office.
- ✓ Insufficient funding and/or requirements creep.
- ✓ Premature attempts to apply off-the-shelf components without fully understanding the system needs.
- ✓ "System shock" arising from too abrupt a transition from the ideal laboratory environment to the harsh realities of real-world applications.
- ✓ Insufficient documentation to support program transitions from R&D phases to production. **[Everett et al., 1996]**[3]

[3] H. R. Everett, R. T. Laird, T. A. Heath-Pastore, G. A. Gilbreath, and R. S. Inderieden. 1996. "Technical Development Strategy for the Mobile Detection Assessment Response System-Interior (MDARS-I). Technical Note 1776 (Aug). Contact authors at SSC San Diego.

A discussion upon these *Lessons Learned* from the same MDARS publication is of sufficient value to quote nearly in total here.

- ✓ *Program managers did not appreciate the issues associated with a software-intensive program.* — Most treated software as if it were magic, and expected unrealistic end results without understanding anything about the process. There was little (if any) appreciation of the costs associated with development, much less maintenance. This deficiency resulted in a lot of spaghetti code that could not be maintained, much less upgraded.
- ✓ *The projects displaying the greatest likelihood of success were relatively small and very focused in terms of their stated objectives.* — With limited resources and experience, it is very prudent to focus on an achievable objective without trying to solve all the problems of the world.
- ✓ *The bigger the performing organization, the lower the chances of success.* — This was especially true in the case of large corporations with high-powered sales and public relations capabilities that had been displaced from other business pursuits (i.e., petroleum industry, nuclear industry, space program) and had no real robotics experience.
- ✓ *The greater the number of active players and organizations, the less likelihood of meaningful developmental results.* — Problems associated with the effective coordination of a large group of geographically dispersed organizations soon overshadows any perceived synergism. There are much more effective ways to achieve the same desired results through technology transfer.

Continuing on, Everett et al. wrote:

> With regard to this last point, there is a strong natural tendency when managing a high-risk new-technology effort to feel that having more players on the team translates to more bases covered, with less likelihood of something falling through the crack. Experience has repeatedly shown, however, that beyond a certain optimal point the reverse is actually true. It is highly desirable to have a broad mix of backgrounds and talents, but it takes a skilled and experienced manager to recognize the point of diminishing returns. The ideal developmental approach provides an optimal mix of both government and industry. Given the limited (and shrinking!) number of adequately trained government employees in the field, this situation is understandably sometimes difficult to achieve.
>
> *Nearly all of the* [previous DoD] *programs were successful in demonstrating technical feasibility, but only a very small percentage were able to demonstrate value added.*
>
> It should therefore be rather obvious that MDARS is not going to be the first to succeed where so many others have failed by cutting corners and eliminating necessary work. Such an approach introduces significant potential for catastrophic failure in a highly visible program. On the positive side, however, a number of very effective strategies have been employed by astute managers with

limited budgets in order to minimize the technical risk and increase the chances of programmatic success:

- ✓ Identify common technological needs and address jointly. — While this sounds good on paper, the recurring problem in practice has been the repeatedly demonstrated unwillingness of different government organizations to work together towards a common goal.
- ✓ Minimize the pressure to let “politics” override sound technical judgment. — This all too common practice has killed more well-intentioned attempts than probably any other single cause.
- ✓ Avoid any tendency to adopt a “not-invented here” attitude. — The first successful robotic fielding, when it comes, will ride the coat-tails of a number of previous attempts, taking full advantage of all the lessons learned. Look the other way and you become a lesson for someone else.
- ✓ Be willing to eat your young. — The technical development team must be constantly on the lookout for newly introduced capabilities, and not hesitate to abandon an in-house approach if better options come along from alternative sources." **[Everett et al., 1996]**

4.2.4.3 How to Come up with Better Solutions

> Start with the end objective in mind, then work backward. Avoid up-front assumptions, i.e. an integrated robot, or a biological approach (neither man-like nor crab-like). **[Schempf, 2001]**

Schempf's warning to avoid up-front assumptions is wise, but keeping any particular objective in mind could defeat that caution. Take, for example, that we want to visit our Aunt Thelma who lives in Minneapolis. In planning our trip, we may be tempted to state that our objective is Minneapolis, for it is a definite location on the map that we know how to find. But this could give us problems, particularly if Aunt Thelma just happened to be vacationing in Hawaii at the time. Rather, we should have understood that our objective was to visit Aunt Thelma, provided that she was accessible.

We use the term *Mine Countermeasures (MCM)*, not fully aware that this term is loaded with bias that may send us where we do not need to go to reach our objective. The biases associated with MCM are that mines, dangerous ones at that, are going to be in place and must be countered. We could counter them by finding them, and then by going around them, or by destroying them in place. But, there are other approaches that could be taken.

One approach could be that we might discourage the initial placement of mines. (We mentioned this possibility first in Section 3.1.1.) One way to state our objective that might eliminate most of the inherent biases would be *no mines*. A similar medical model of this approach is the prevention of infections through inoculations. Inoculations prepare the natural body defenses to eliminate the pathogen upon its subsequent introduction. Innoculations save a great deal of effort later in terms of countermeasures to infections.

> When defining your program, write the concept of operations (CONOPS) first and then invite industry in to comment. **[Dodd, 2001]**

While industry is pragmatic, it is also profit-oriented. The concept of operations, if defined first, could drive the search for a cost-effective solution. Otherwise, the profit-effective solution could drive the operational concepts and associated requirements.

> A concept of operations should consider both day and night conditions, and different water/bottom conditions. **[Landry, 2001]**

> Ensure that program managers wait until their operational requirements document (ORD) is complete and approved before beginning to develop a final system. Much energy and resources could be wasted by a PM trying to jump ahead of events without an approved ORD. **[Adams, 2001]**

> Keep the user involved at all times when decisions must be made on design, limitations of the system, immaturity of technology that affects the system, appearance and maintenance support. Sometimes the user will have a difficult time understanding limitations due to technology, cost or schedule. There may come a time when you need to call in an objective third party to hear both sides of an issue to get a different perspective. This third party must be neutral and an expert in the area of concern. This outside voice may offer insight or experience that will be useful to both sides. However, at the end of the day, the user must be satisfied with the system and understand why he made a tradeoff. **[Folk, 2001]**

4.2.4.4 Value and Risks of Demonstrations

> Early user involvement is important, but be aware that expectations may exceed system capabilities in early demonstrations. **[Landry, 2001]**

> The biggest problem encountered in the MPRS prototype demonstration was inadequately trained operators, who have little or no troubleshooting experience with the unique system. **[Bruch et al., 2000]**

> Expect a large amount of the available resources to go into debugging, and demo preparation. **[Gage, 1999]**

But, this may be true only because too few resources were put into development of a brilliant universal overarching architectural scheme and its testing under all realistic operational conditions.

The success of a demonstration is often state-dependent, that is, dependent upon the state of the developer/demonstrator. Adequate attention to coordination, team management, and training are essential.

During demonstrations, the urge is to attempt too much, which increases the likelihood of failure in a complex and inadequately tested system. When the purpose of a demonstration is to show successful capabilities, ambitious objectives must be restrained.

> In operational testing, plan for bad weather. **[Gothard et al., 2001]**

> One serious problem with the Demo III design or developmental process was that one problem was attacked at a time. There was no general solution. Some problems did not receive consideration until they appeared unexpectedly in the environment. **[Haug, 2001]**

This systematic approach to problem solving would ordinarily be applauded if the subject system was simple or if the number of determining factors in the outcome of any trial were few. But the natural environment is quite complex, and the requisite number of component parts that participate in any one operation are considerable. One fundamental problem with the DARPA/Army Demo series is the extremely ambitious objective to assemble an artificial system that demonstrates pretty sophisticated human-like abilities. What makes the objective extremely ambitious is that it was attempted without first having been able to demonstrate the integrated repertoires of any number of less capable species that none-the-less traverse difficult terrain, avoid obstacles, acquire and pursue targets, and defend themselves.

4.2.4.5 Value of Prototyping

> Close the loop with users throughout the design and development process. Implement phased rapid prototyping and provide prototypes periodically to the users for evaluation. Build a strong relationship with the user, educate the user on relevant technologies, and become educated on the user's mission and requirements. Use this relationship to make good financial and technical tradeoff decisions. [**Everett et al., 1996[4]; Heath-Pastore, 2001; Knichel, 2001**]

> This has been especially helpful in defining paragraph 4a of the Operational Requirement Document[5]. **[Adams, 2001]**

> DARPA has been a good source for vehicles for this purpose. **[Knichel, 2001]**

4.2.4.6 The Value of Modeling and Simulation

> Modeling and simulation can give insights into potential system performance and methods of employment. **[Landry, 2001]**

Thus, resources for Modeling and Simulation (M&S) should be allocated quite early in the program.

> M&S may substitute when prototypes are not available. **[Hudson, 2001]**

> The UGV/S JPO Robotic Acquisition through Virtual Environments and Networked Simulations (RAVENS) initiative is designed to assist in the following:
> - ✓ Requirements development
> - ✓ Technology development and evaluation
> - ✓ Risk reduction

[4] *Ibid*

[5] Paragraph 4a of the Operational Requirements Document shall contain information on the required performance capabilities of the system to be acquired in relationship to its relevant mission scenarios, and include key performance parameters. CJCSI 3170.1A, Requirements Generation System, 10 August 1999.

- ✓ Tactical innovation
- ✓ Operational assessment. **[Hudson, 2001]**

Existing simulations may need to be re-scaled to accommodate factors relevant to operation of robots. **[Hudson, 2001]**

4.2.4.7 Requirements Process

Getting users involved early keeps the program relevant, but users are not very patient and expect a lot more than the vehicles can deliver. **[Haug, 2001]**

Must understand (and contain) the user requirements. Useful to scope the problem in terms of mission scenarios. This will make it possible to clarify the payback – e.g. lives saved. **[Toscano, 2001]**

Deal with the environmental requirements from the get go. Don't put it off. The cost to add it in after the design is completed is considerably more than doing it up front. It will add some costs to the system but will greatly enhance its ability to operate in rain, cold, snow, etc. **[Anderson, 2001]**

In defining the requirements:

- ✓ Consider all possible end users, have they met and agreed upon the requirements? Some systems may have multiple requirements for different users.
- ✓ Consider all possible operating temperatures? Does the system truly have to operate at –25F?
- ✓ Consider EMI. Has the IPT determined what operating systems may affect your system and will your system interfere with other systems in an operational scenario? Hardening for EMI can be costly but necessary; the user must determine what level of protection is required.
- ✓ Consider Human Factors. Have soldiers evaluate and comment on your design at ever opportunity. Especially important when designing a system that must be operated manually or by robotics depending on the situation. The robotic operation must emulate the manual operation as much as possible.
- ✓ Consider all possible restrictions on radio frequencies used by your system. In peacetime, soldiers must train. Can your frequency be used overseas and in the United States?
- ✓ Consider Built-in-Test (BIT) capability, though this will be software intensive.
- ✓ Consider early consensus on hardening requirements: Must your system hold up in tough terrain environments that will vibrate the system often and continuously? Severe vibration will cause damage over time. **[Folk, 2001]**

But, avoid war-stories as the basis for requirements. **[Schempf, 2001]**

Make sure, and I reiterate, make sure that the organization that is developing the requirements understands the limitations of technologies. We call this expectation management. Work closely with them in developing their requirements. **[Anderson, 2001]**

Separate the *must have* requirements from the *like to have*, then compare the cost/benefits of the *like to have*. Attach a mission scenario/justification to each *must have* requirement. Don't let outliers define the requirements. Go after the most common problem. Don't worry about exceptions or clever means to counter. **[Schempf, 2001]**

The Kepner-Tregoe (KT) decision analysis process for trade studies involves the following steps:

- ✓ determine scope.
- ✓ list the musts (those metrics if failed eliminate the candidate solutions).
- ✓ list the wants and their relative weights. [low risk and low cost may be a want or a must]
- ✓ identify the candidate solutions and their characteristics with respect to the musts and wants.
- ✓ filter the candidates with respect to the musts.
- ✓ score the remaining candidates with respect to the wants and total.
- ✓ perform cost and risk analysis on the top scoring candidates. [if not already considered] **[Gothard et al., 1998]**

Prioritize requirements. Implement the critical features first. Avoid the temptation to add bells and whistles before attaining basic, required functionality that is reliable. **[Heath-Pastore, 2001]**

It is valuable to understand the technology readiness for the requirements, and the relevancy and adequacy of the requirements for the objective.

For example,

…detecting mines is extremely difficult - are the requirements consistent with the objective. **[Weisbin, 2001]**

Can the requirements be met with the current state of the technology?

If the VSW MCM system is expected to be fielded in three years, then there is an implicit assumption that the required technology is ready today. **[Weisbin, 2001]**

Put together an integrated system concept for all of the required capabilities, and run that by the users for reality checking. Ask if it is too big, too expensive, too complicated, too hard to use, etc. **[Schempf, 2001]**

If technology development necessary to accomplish the objective is too expensive,

What are the de-scoping issues, plans? **[Weisbin, 2001]**

State the level of reliability required and do not compromise early in the effort. DoD has equipment that has designed in poor reliability which has resulted in lack of serviceperson or commander confidence in the system. **[Adams, 2001]**

UUV system countermeasures and survivability should be considered early in the program. **[Landry, 2001]**

Cost is an independent variable. **[Landry, 2001]**

Yet different costs may be traded.

In the area of survivability, it is better to keep cost low, then the product can be more dispensable compared to the costs of taking it out of action. Another important comparison however is the cost of the consequences of the threat. A relatively cheap mine could sink a ship, therefore it might be better to neutralize the mine with an expensive UUV in order to save the ship. **[Milcetic, 2001]**

The robot product must be useful and worth its price. **[Gage, 1999]**

Expect and allow for requirements creep. **[Toscano, 2001]**

The probability of achieving performance objectives in a robotic system, when there exists uncertainty whether or not the required technology is sufficiently mature, can be increased using the following process as described in the MDARS strategy publication:

- ✓ Identify the actual user requirements and describe these in terms of needed system functionalities.
- ✓ Match these to the specific technological needs required to achieve successful implementation.
- ✓ Break these technological needs down into three categories:
  - Those that currently exist as state of the art (i.e., commercial-off-the-shelf-technology).
  - Those likely to come along in the near-term (i.e., within the desired development schedule).
  - Those that are project-specific and unlikely to be otherwise addressed by industry or academia.
- ✓ The highest priority for allocation of government resources should naturally be assigned to those technical needs falling into the last category above. **[Everett et al., 1996]**[6]

The Program Office may quickly find that a large investment in technology R&D will be required to meet system performance objectives. As long as the performance objectives do not violate the laws of physics, the Program Office may safely assume that a technological capability could be found that will satisfy the requirement. Depending upon the criticality of achieving those objectives, the Program Office can then choose one of the following:

- Table certain performance objectives as currently unfeasible for lack of technological capability - least costly and least effective.

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[6] H. R. Everett, R. T. Laird, T. A. Heath-Pastore, G. A. Gilbreath, and R. S. Inderieden. 1996. “Technical Development Strategy for the Mobile Detection Assessment Response System-Interior (MDARS-I). Technical Note 1776 (Aug). Contact authors at SSC San Diego.

- Encourage and/or otherwise support DARPA, ONR, and other 6.1-6.3A projects to accelerate development of the needed technologies - most expedient.
- Invest program dollars directly into technology development - most costly and most effective.

4.2.4.8 Managing Cost and Schedule

In pursuing performance objectives it is hard to keep costs down, and to keep the technology simple. **[Witter, 2001]**

When managing schedule and performance goals, it is better to reach the goals and let the schedule slip. **[Toscano, 2001]**

Many surprises can impact cost and schedule: the redesign of boards is very time consuming; often they will not work the first time as testing will uncover “bugs” in the system. Expect and plan for “time and money” to do reasonable “test-fix-retest”. These are complicated systems that require a certain degree of time dedicated to testing and redesign. **[Folk, 2001]**

Determine and state cost and performance objectives early to guide the PM in developing the schedule. If the schedule considerations dominate the program decisions, there is a good chance that the system will either cost more than the customer expects or may have less performance than desired or needed. **[Adams, 2001]**

It was useful to specify that the contractor provide a second prototype, for the engineering prototype will have to be modified during operational testing. **[Folk, 2001]**

A successful prototype is generally dependent upon who does the work. How will the performer (contractor) be selected? **[Weisbin, 2001]**

4.2.4.9 Contracting

Consider when selecting a contractor:

- ✓ Program execution is easier if the same contractor can do both R&D and production. If the contractor is strictly R&D, do they have competent people and facilities to build a sound prototype?
- ✓ Does the contractor have a placed to test his prototype in a field environment or will the first test be at a government facility/range?
- ✓ What is the contractor’s plan for quality assurance; is the QA plan already implemented and in use by the contractor?
- ✓ What is the contractor’s standard for software engineering? Do they have engineers that can truly check the work of programmers and do they have appropriate diagnostic equipment to run tests?
- ✓ What is the contractor process for configuration management; is the CM plan already implemented and working?

- ✓ What are the contractor's resources? Small contractors are prone to promise more because survival is at stake. Will this contractor “close his doors” if he fails on your contract? **[Folk, 2001]**

As always, competition is the key to getting a good contractor. The robotics community should pursue contracting strategies that broaden the commercial base of its suppliers.

Reliability of robotics-related hardware is a major concern to many academic developers. These developers also voiced a common complaint about the poor support they received from suppliers, while acknowledging that the reason for this may be the non-commercial nature of the industry.

4.2.4.10 Maintaining a Successful Program

Need to introduce some low-risk robot applications in order to change the culture and pave the way for more ambitious projects. i.e. the robotic follower ATD. **[Bornstein et al., 2001]**

The most important criteria for a successful program is producing an end product that the user will use and appreciate. **[Everett et al., 1996]**

Behavioral robustness is required if mobile robots are to find viable markets; the designer must accommodate the full range of variability within:
- ✓ The manufacturing processes: no handcrafting
- ✓ The target operating environments: no manual "tuning" **[Gage, 2000]**

Select a niche mission that can be accomplished cost effectively. **[Toscano, 2001]**

Do not say "reduce people", say instead, "make them more effective". **[Bonheim, 2001]**

Coordination with other robotics programs can be a problem. An effective approach is to share funding, or share people. **[Toscano, 2001]**

Personalities are the key to cooperation with other defense programs. **[Witter, 2001]**

Personal relationships work best when trying to influence DARPA to coordinate with your program. Then come to DARPA with a developer. **[Dodd, 2001]**

The PM or his representative should participate in the Interagency Security Technology Exchange
- ✓ keep informed
- ✓ avoid paying twice for the same capability
- ✓ helpful to share programmatic information as well as technical information **[Witter, 2001]**

Continuously survey the technology readiness, constantly visit the developers, keep experts as consultants. Set up an advisory council. Council members will generally

fund their own participation just to keep association with the program. **[Jenkins, 2001]**

Permit no harm to come to domestic interests during development, testing, or operation, and threaten no harm to friendly operations. **[Toscano, 2001]**

Congress and most constituents are shy about the placement of weapons on robots. **[Morrison, 2001]**

Early UGV programs lost funding when program managers proposed arming the vehicles. Users are content to "see better", rather than to "shoot sooner". **[Haug, 2001]**

There are at least two practical factors that militate against arming a robot: Inadequate agility – the robot will be subject to hostile fire if it reveals its position. Inadequate physical security – the robot cannot adequately perceive or respond to immediate threats in its environment without human support. **[Haug, 2001]**

When faced with the need to pursue something that is politically sensitive or culturally controversial, deflect cultural resistance to another issue that is inconsequential and to which your program can later yield. **[Dodd, 2001]**

Money is the most critical programmatic problem. **[Toscano, 2001]**

Maintain the stability of the funding base **[Jenkins, 2001]**

Identify a champion and nurture support from the top. **[Toscano, 2001]**

It would be wise to look to future issues just in case you become successful with the present project objectives. **[Toscano, 2001]**

4.3 Technologies

4.3.1 Lessons Relevant to Sensor Technologies

Apply the right sensor for the type of control required **[Gothard et al., 1993]**.

Effective fusion of redundant sensors is the key to robust operation. **[Everett, 2001]**

Be prepared to replace some sensors that are found inadequate, because the final environment is very hard to predict **[Gothard et al., 1993]**.

Don't depend on a single sensor technology, sensors LIE! **[Klarer, 2001]**

If the environment changes, go back and check each sensor to see if the change had an adverse effect on the sensors. **[Gothard et al., 1993]**

Adaptive sensors would help greatly with this problem.

Choose sensor phenomenology that differentiates vs. "just detects", that penetrates environmental and terrain features as required, and minimizes algorithmic processing to get useful information. **[Gothard et al., 1998]**

Demo III views the autonomous navigation problem as a feature classification problem. **[Rosenblum et al., 1998]**

Autonomous robotic mobility requires redundancy in both sensors and algorithms employed for both reliability and robustness. **[Rosenblum et al., 1998]**

Redundancy in sensors permits a combination of phenomenologies of the sensors that implicitly provides contrast to easily segment out the hazardous features of the scene. **[Rosenblum et al., 1998]**

Criteria include reliability, robustness, self-adapting, and low cost. Requirements for component accuracy should be reduced while increasing simultaneously the accuracy of the resultant capabilities. Similar to the objective to reduce accuracy is to reduce the need for data resolution. **[Rosenblum et al., 1998]**

In multi-sensor systems, difficulty is encountered in correlating sensors with respect to the same target. **[Thorpe, 2001]**

If a complex robot is to operate robustly, its world model must take adequate account of the relevant dimensions of variability of the environment, as they will be reported by the sensor subsystems.

- ✓ A robot's world model is much simpler than a human's.
- ✓ Unintended aspects of the model can creep in as consequences of various software design decisions
- ✓ The developer must understand the limits of his system's world model **[Gage, 2000]**

Consider chemical sensors, consider a fish that is either trained or controlled by implanted electrodes. **[Brooks, 2001]**

The logic behind the above suggestion is that most unique artifacts in the water should release traceable chemicals that will diffuse along a gradient. Most animals, both marine and terrestrial, are designed to track along such gradients. The trick is to train a fish to orient to a particular chemical and then to control its tropic behavior so that it approaches the source of the diffusion. The fish could loiter about the source until it expires or until the tropic control stimulus is removed. Such fish could also involuntarily transport pingers or detonators. Small sharks or rays might be good candidates. Because of the natural abilities of the fish to negotiate obstacles, swim in and against currents, and find sources of energy (feed themselves), their employment could already solve many of the troublesome problems facing the use of small unmanned underwater vehicles. With the proper placement of electrodes in the fish brain, training requirements could be minimized, thus significantly reducing costs.

Figure 12. Manta Ray candidate for hybrid VSW MCM application.

Some other issues that must be addressed in this hybrid approach are reliability, communications/control and re-tasking, zone coverage, and recovery and/or disposal of surplus agents.

Other common residents of the shallow water and SZs that might be used in mine detection and neutralization include lobsters and octopi. The latter have excellent visual and tactile abilities, and can be operantly trained and controlled by electrical brain stimulation. DARPA is exploring technologies relevant to this approach [DARPA].

Tactile sensors of equivalent utility for UUVs do not currently exist.

> Tactile sensors are not well developed. But one strategy might be to tow in a sensor net that detects targets by contact and provides simultaneous mapping information. Like a spider web the sensor net could guide other vehicles that place charges on verified obstacles and mines. **[Schempf, 2001]**

4.3.2 Lessons Relevant to Communications and Control Methods

> The biggest risk area for the overall unmanned systems area is adequate assured communications capabilities and the development and fielding of new, mature command and control capabilities that are specifically capable of providing the man-unmanned team interfaces and capabilities without over-burdening the soldiers and staff with unnecessary interruptions or workload. **[Dodd, 2000]**

> Antenna height is one of the most important aspects of RF performance. If you want to enhance your data-link performance, raise the antenna several wavelengths above the nearest surface. At the 4.4-5.85 GHz band we implemented a pneumatic mast to raise the antenna to a height of 43 feet. Works great! Antenna directionality (gain) is next. Must have gain at least on the receiving end. A method to put directional gain on a moving vehicle, cheaply and easily, would be a great enhancement. Utilize the lowest loss cabling and connectors you can find. When you raise the antenna you add cable length. If the correct cable is not used, your losses can offset the gains you get from height. Utilize filtering and pre-amps to the maximum. You can't filter too

much. Make sure the antennas are mounted correctly on the robot and the operator control unit. We had an occurrence where we were creating nulls in the antenna pattern because the antenna system was not addressed during the development of the overall system. It has to be an integral part of the system engineering process. Conduct antenna pattern testing early in the design to ensure that the problem is not present. **[Anderson, 2001]**

I've seen too many systems that REQUIRE high bandwidth communications such that they are hamstrung unless they have multi-megabit bandwidth. Our approach has been to drive communications bandwidth requirements down as far as possible, and force ourselves to live with reduced communications. This has driven our algorithms and controls approaches to be efficient and effective. My advice: DO NOT LISTEN to anyone who tells you that communication bandwidth reduction is not an issue...it is, it will always be, and it will only get worse over time. **[Klarer, 2001]**

Define (or adopt) a communication interface between the command and control station and the remote vehicle that supports a layer of abstraction. The future can bring changes to both the vehicle and the control station or another vehicle type may be desired/required. This is reasonable to accommodate with a higher-level interface specification defined, but nearly impossible if the control station and vehicle have a low-level intertwined relationship. **[Heath-Pastore, 2001]**

One of the major concerns of military decision-makers relative to the deployment of UGVs is the problem with maintaining reliable communication. Not too long ago (early 90's), it was nearly impossible to have multiple indoor robots or UAVs communicating at a decent rate without severe problems, as was observed regularly at competitive robot events. Georgia Tech adopted commercial ISM band frequency-hopping data links for this application, and we've been quite satisfied with the performance of this equipment in relatively benign indoor and outdoor conditions, including both ground and aerial vehicles. But the difficulty of maintaining/configuring point-to-point links, combined with the trend towards simultaneous operation of more vehicles, has driven me toward a related COTS technology, 802.11 wireless LAN. The ease of use is much greater, but with significant reduction of range (from 0.5-1 mile down to 100-500 feet, typically). Raytheon developed longer-range down-converters that could be used as front-ends on COTS 802.11 devices, and these were demonstrated successfully at the DARPA Tactical Mobile Robotics (TMR) demonstrations in 2000. It's not clear how applicable any of these RF experiences would be to UUVs. As an occasional diver, I'm aware of the absorption of visible light (most strongly toward the red end the spectrum), but I have wondered whether there is some visible or near-visible band that would be suitable for underwater communication, at least in short-range applications such as the coordination of many EOD UUVs in a harbor operation. Also, it's worth noting that a great deal of cooperative behavior can be accomplished without explicit communication. Simply by observing other robots (or the effects of other robots on the environment), a robot can implicitly understand the intents and actions of other robots. This phenomenon is observed in biological systems (schooling, flocking, coordinated predator responses, etc.), and we have utilized it in robot foraging experiments. **[Collins, 2001]**

Visual coordination is undeniably involved in the schooling of fish. Fish also communicate using modulations of electrical potentials in the lateral line organ for coordination during schooling. These methods work primarily on nearest neighbors and poorly at a distance. Whether information is broadcast by whole body behaviors or by modulations of electrical potentials, the observation of those changes of state are necessary for communication, and it is the difficulty of RF transmission in the water that makes the reception (observation) of RF-mediated communications difficult.

> A major drawback to the digital video system used in the MPRS prototype was the high bandwidth requirement and hence the requirements for a WLAN modem and the high frequencies employed by these radios. Because of the low-power and high-frequency characteristics of these radios, the communications opportunity was generally limited to LOS. However, the tunnel environment often acted as a wave guide, facilitating transmission. **[Bruch et al., 2000]**

> The frame rate of the visual feed to Demo III operators was too slow **[Burns et al., 2000]**.

Of the information to be communicated, we may define three categories:

- Vehicle status.
- Mission status.
- Environmental status.

> Like most major centers of mobile robot research, Georgia Tech adopted behavior-based control techniques, but unlike many others, they have long championed the use of hybrid architectures which also include a deliberative supervisory component (like the higher-level mapper capability mentioned in the previous section). Hybrid architectures provide the robust behavior and quick response characteristic of behavior-based control while still allowing for organized planning and high-level structured behavior. The complexity which inevitably results from a sophisticated hybrid control architecture can be mitigated with machine learning techniques. Currently, in the DARPA Mobile Autonomous Robot Software (MARS) program, we’re integrating learning at five levels within the architecture, from online adaptation of behavioral parameters all the way up to techniques for improving the skills of the human who defines missions. **[Collins, 2001]**

> The biggest risks for the overall unmanned systems area are adequate assured communications capabilities and the development of new, mature command and control capabilities. **[Dodd, 2001]**

Again, what makes communications, command, and control so important in unmanned systems is the lack of reliable autonomy, versus automaticity, in the unmanned systems. Automatic systems will go their preprogrammed way unless interrupted by exceptions, at which point, the operator is called back into the control loop. Without communications, the interruption could be quite extended. Less automaticity and greater autonomy would permit the unmanned systems to achieve mission objectives by exercising real-time re-planning and adaptations to changing and unexpected conditions.

Without autonomy, the robots are simply extended tools. With automaticity, the robots are fancy tools, but tools none-the-less, ultimately dependent upon human control, and upon communications to maintain that control.

If our communications capabilities are going to be in doubt, then we must be willing either to reduce our remote functionality or to permit the remote autonomy.

4.3.2.1 Methods of Control

> On our operator control units, we typically have all sorts of buttons, switches, displays, etc. The more you have, the more problems you have. You have problems with joysticks breaking, displays not working in cold weather, water leaks, etc. Think minimum on switches, etc. Maybe have some sort of software interface or touch screen. We are developing a system now with only a touch-screen for the operator to interface with. **[Anderson, 2001]**

> Make the control system as plug and play as possible. Modularity is great! Our experience is that when we give a soldier/marine a system with capabilities, they always want to add more. Think modularity and expandability. Logistics guys love this too. **[Anderson, 2001]**

> Conventional control methods have proven perfectly adequate for everything we've done to date...... elaborate or complex schemes are great conference paper material but are not necessarily appropriate for our customers. For ANYTHING military, you MUST prove stability and robustness for safety and reliability considerations. **[Klarer, 2001]**

> Robot control strategies must expect the unexpected, prepare for uncertainty **[Thrun, 2001]**

4.3.2.2 Mixed Initiative Control

> A major research question remains: how to handle mixed initiative control? **[Swinson, 2001]**

Mixed initiative is the situation when the human operator and the onboard control algorithms are simultaneously attempting to direct the vehicle.

> No one will let absolutely dumb vehicles into the operating environment without complete human control, but the vehicles must have some minimal level of competency, i.e. obstacle avoidance. **[Swinson, 2001]**

Humans are far from being error-free and high-reliability cohorts. Thus, with humans introducing an additional element of uncertainty into the control loop of a vehicle that is supposed to reactively negotiate in real-time obstacles and other unknowns in its path, robots may have to exercise more adaptive capabilities than if they were left to their own devices.

> We spend a lot of money on the platforms, but do not get to address the critical issues of control. **[Swinson, 2001]**

Related to the problem of mixed initiative is the problem of embedded software.

> Part of the problem of embedded software is the communication among developers, because people with domain experience in the application have no software competency, and because the good software engineers do not understand the physics and engineering problems. Second is the problem of how to instantiate the different levels of competency. **[Swinson, 2001]**

4.3.3 Lessons Related to Other Technology Issues

4.3.3.1 MDARS Lessons Learned

The MDARS-I project literature refers to an experience in which the robot failed to perform adequately after it was moved from one developmental environment to a different test environment. The MDARS-I team called this phenomenon *system shock*, and considered it a problem of fundamental importance and common occurrence:

> ✓ The MDARS-I developers learned that moving a robot from one environment to another created unanticipated problems; typical causes include:
> ✓ hardware and software errors that had not been manifested in the previous environment;
> ✓ sensor modes or processing algorithms tuned too tightly to specific characteristics of the initial development environment;
> ✓ subtle interactions between limitations in multiple hardware and software components . **[Gage, 2000]**

> A key lesson is that system robustness can only be ensured by exhaustively exercising its operational capabilities in a number of diverse environments. This approach helps uncover latent system hardware deficiencies and software implementation errors not manifested in the initial system hardware or initial development environment. **[Everett et al., 2001]**

The MDARS-I team suggest a solution to the fundamental cause of "system shock" in their next paragraph.

> A human's perceptual capabilities are powerfully adept at characterizing both the similarities and differences between various features of his/her environment – at detecting both the general rule and the specific exception to it. A robot's sensory inputs, on the other hand, are far more limited, as it can interpret these inputs only up to the limits of its environmental model. **[Everett et al., 2001]**

But the authors' explanation is that "the robot's implicit world model is not rich enough to support the behaviors required by the application."

An alternative explanation is that the world models that the human programmer and users are able to talk about have little to do with adaptability. In this alternative, adaptability is dependent upon the presence of fundamental reflexes that subserve all developments and employments of higher world models in any member of any species.

Without the appropriate fundamental reflexes installed in a robot, the programmer and user will be continuously trying to predict the exceptions to high-level rules that the robot will encounter, and predict the appropriate changes in operational parameters that will compensate for those exceptions. The attempt to predict compensatory adjustments must be performed open loop, and thus without the possibility of feedback, is at high risk for failure.

The authors conclude the following:

> Behavioral robustness is required if mobile robots are to infiltrate viable markets. Truly practical robots must be mass producible, rather than handcrafted, and they must function acceptably over as wide a range of environments as possible without excessive manual tuning. Thus the designer of mobile robotic hardware and software must accommodate the full range of variability within manufacturing processes and within target operating environments, or face the consequences in the form of unreliable real-world performance. **[Everett et al., 2001]**

The solution is to provide a basis for perception and performance that is not entirely dependent upon a specified world model.

4.3.3.2 Human/Robot Interactions

> Mobile robots deployed in real-world applications must of necessity be capable of successfully interacting with humans, the operators who task them and monitor their performance as well as those who by plan or happenstance share the robots' workspace. **[Everett, 2001]**

The design of the robots and the concept for their operation must consider not only the habits and requirements of their operators, but also the habits and propensities of people who might encounter the robots during mission performance. People in the robot's environment could be cooperative, indifferent, hostile, or just curious. The expression of each of those different attitudes could have significant consequences on the safety and effectiveness of the robot.

The MDARS project also discovered that the dual use of robot sensors for automatic robot navigation and teleoperation posed difficulties. The problem here, though, is due more to an incomplete satisfaction of operator information needs. Teleoperation presents many difficulties that can be either mollified or exacerbated by robot-initiated behaviors. Many computer users experience something similar to this when keyboard commands are ignored by their computers, or when something quite unexpected results from a commanded action, either of which could have saved the user from a greater grief, had the user been aware of his action's consequences.

Developers of robots must remember that their users have not had the benefits of many years of developmental experience with their robots. Little about the robot should be assumed as intuitive to the user. In summary, the authors advise the following:

- ✓ Display information in terms meaningful for the operator: rather than presenting a number representing battery voltage, show percentage of charge remaining, or operating time remaining, preferably in graphical format. Use color to

differentiate "plenty of power" from "power getting low", and add an audio alert for "power dangerously low".

- ✓ Make clear to the user what action(s) he or she is expected to perform. If a simple acknowledgment is desired, then the system should display a single big "OK" button, with the cursor already placed on it. Do not display options that are not currently available as grayed-out icons—make them completely invisible. Provide a brief top-level explanation of what is going on with graphics or large bold text, with supporting details available but not intrusive.
- ✓ Automatically monitor system state proactively and defensively.
- ✓ Understand the users—understand the job they are assigned to do, how they do that job, and their level of education, training, and experience.
- ✓ Second, respect the users—listen to their concerns and suggestions. And remember that they will have the final say in judging whether the robot application is a success or failure.
- ✓ Third, support the users—make it as easy as possible for them to provide the appropriate inputs to the robotic system in every situation, and for them to be successful in doing their jobs.
- ✓ Finally, work very hard to make the system "user-proof"—make it as difficult as possible for them to make inappropriate inputs to the system. **[Everett et al., 2001]**

4.3.3.3 Mobility and Methods of Locomotion

> RSTA is a most difficult task. Two of the biggest problems are mobility and communications. In smaller systems, power becomes a major consideration. **[Toscano, 2001]**

In urban search and rescue (mostly work under rubble following disasters such as a building collapse), an environment not too dissimilar to the underwater environment with regard to physical constraints, the major problems are communications with the robot, sensors, power density and duration, and just getting around in the rubble. Disabled robots are as good as lost.

If an agent is competently mobile, then it should be able to get along without constant supervision. This mobility would reduce the dependence of the vehicle upon communications. But we have seen in the example of the urban search vehicle, that even excellent communications cannot salvage a vehicle that becomes stuck in rubble. Mobility as a system capability should be given a higher priority than communications.

If we are going to use machines in the defense of our resources, whether those resources are fixed and our adversaries are mobile, or our resources are mobile and the threats to our resources are fixed (as are some mines), and if we do not wish to man those machines, then we must make sure that the machines in our absence have adequate mobility, and adequate information gathering and processing functionality to accomplish effective tactical maneuvers that maintain their separation from the threats.

Our machines cannot now independently govern their own mobility. As simple a requirement as obstacle avoidance in an untended machine is extremely difficult to provide in unpredictable real-world environments. The problems of machine target detection, and of

machine prediction of the behaviors of other mobile agents, have largely remained unsolved. Rather, machines require intensive and costly human attention for control in any but the most structured and benign environments. The remote monitoring and control of an unmanned vehicle actually increases human labor and decreases the overall effectiveness of the system compared to a manned presence. This result is the consequence of the increased difficulty of human intervention in events beyond normal human sensor ranges and beyond the normal human reach. Thus, at the present, our systems of remotely controlled machines and operators are at a great disadvantage when assigned to the tasks of protecting and preserving our resources under competition with highly maneuverable manned threats.

> The MPRS project discovered that its prototype robot, the URBOT, was not fast enough to keep up with the momentum of an attack. During an attack on a city, momentum is everything; if someone or something cannot keep up it gets left behind. **[Bruch et al., 2000]**

Tactically speaking, a sluggish agent gets out-maneuvered, overtaken, and overpowered.

Professor Benjamin Brown of the Robitics Institute at Carnegie Mellon University has produced and interesting mobile robot composed of a single gyroscopically controlled wheel.

> Gyrover is a single-wheel robot that is stabilized and steered by means of an internal, mechanical gyroscope. Gyrover can stand and turn in place, move deliberately at low speed, climb moderate grades, and move stably on rough terrain at high speeds. It has a relatively large rolling diameter which facilitates motion over rough terrain; a single track and narrow profile for obstacle avoidance; and is completely enclosed for protection from the environment. **[Brown, 2000]**
>
> In addition to those advantages cited above for a single-wheel vehicle, there are potentially a number of additional advantages to this concept over multi-wheeled vehicles:
>
> - ✓ Gyrover is resistant to getting stuck on obstacles because it has no body to hang up, no exposed appendages, and the entire exposed surface is "live" (driven).
> - ✓ The tiltable flywheel can be used to right the vehicle from its statically stable, rest position (on its side).
> - ✓ The wheel has no "backside" on which to get stuck.
> - ✓ The entire system can be enclosed within the wheel to provide mechanical and environmental protection for equipment and mechanisms.
> - ✓ Gyrover can turn in place by simply leaning and preceding in the desired direction—with no special steering mechanism—enhancing maneuverability.
> - ✓ Single-point contact with the ground eliminates the need to accommodate many contact points and simplifies control.
> - ✓ Full drive traction is available because all the weight is on the single drive wheel.
> - ✓ A large pneumatic tire may have very low ground-contact pressure, resulting in minimal disturbance to the surface and minimum rolling resistance.
> - ✓ The tire may be suitable for traveling on soft soils, sand, snow or ice; riding over brush or other vegetation; or, with adequate buoyancy, for traveling on water. **[Brown, 2000]**

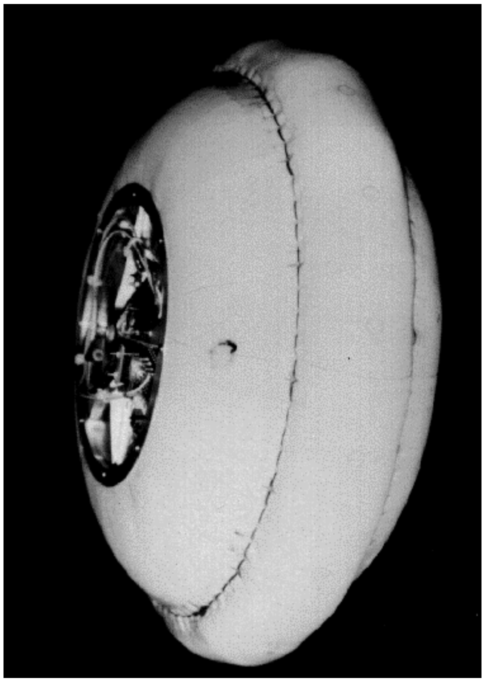

Figure 13. CMU GYROVER.

SANDIA National Laboratories has invented a combustion-powered hopping platform under DARPA sponsorship. The platform was designed for military surveillance applications **[SANDIA]**. Hopping may be the next best thing to flight to avoid obstacles on the ground, but control is lacking during the ballistic phase of the hop. Hopping should have promise as a launching mechanism and as an escape mechanism. The unpredictability of hopping could be a benefit for self-preservation. Insects suffer no ill effects of random landings because their mass and velocity products are too small. Similarly, only the smaller robots should be able to take advantage of hopping for mobility. The SANDIA hopper represented in Figure 14 performs 100 jumps from 10 to 20 feet in the air on a single tank of fuel.

Figure 14. SANDIA researcher Gary Fischer's combustion-powered hopping robot.

4.3.3.4 Power Technologies

> Commercial battery technologies are getting pretty good, we've stuck pretty much with lead-acid gel cells for all but the most demanding of applications simply due to their simplicity and availability. More exotic technologies with higher power density have pitfalls that can be highly problematic, and require things like automatic shutdown to prevent over-current conditions. **[Klarer, 2001]**

SANDIA Laboratory has experimented with fuel cells in the SANDIA RATLER vehicle. Several important lessons were learned, but are as yet unpublished. Interested parties should contact Paul Klarer at SANDIA for more information. **[Klarer, 2001]**

Fuel cells produced by Ball Aerospace **[Ball]** were examined by SSC **–**San Diego for use on the MPRS platform, configured as the URBOT.

> The fuel cells were powered from a small high-pressure hydrogen tank, drawing oxygen from the atmosphere. We used the 50W version to power the motors of the Urbot. Because of noise from the motors, the electronics are powered by a separate battery. The Urbot ran fine with the fuel cell (maybe even a little better than off the battery). The energy density of the fuel cell itself isn't quite high enough yet - I think we need approximately a 200W burst to climb over obstacles. The 100W version they had would have taken up more than a third of the payload compartment without the fuel. As an alternative, we could use batteries to directly power the motors and use the fuel cell to power the electronics and to charge the motor batteries whenever the robot was stationary, similar in concept to the hybrid power systems on the new gas-electric cars. However, this would take some relatively sophisticated (and space consuming) electronics to manage all power switching and battery charging. The current fuel types aren't particularly dense (energy wise) and could pose a significant risk on the battlefield. Use of the methane fuel system, now under development, may improve power density. This technology has potential but needs to be developed further before it will be mature enough to implement on the MPRS. **[Bruch, 2001]**

> Think power management. Lots of times we have developed systems and not considered battery management like we should have. Power management also needs to be an integral part of the system engineering process. **[Anderson, 2001]**

The importance of energy reserve for a mobile agent cannot be overstated. For the UGV community, there have been few options. The UUV environment is even more constrained. The problem can be approached essentially in three ways:

- Increase energy capacity.
- Decrease energy demands.
- Increase energy availability.

System designs should endeavor to optimize at least two of the three approaches.

4.3.4 More Technical Challenges

Challenges are real-time processing and scalability. **[Sukhatme, 2001]**

Challenges are soldier/machine interface, machine perception, and intelligent control. **[Bornstein, 2001]**

- ✓ A most salient problem is real-time resource allocation, or dynamic mission planning
- ✓ must be able to rearrange plans during operation
- ✓ the problems scale badly, they are combinatorial
- ✓ each instance requires a unique solution
- ✓ the whole problem is NP complete
- ✓ worst case complexity is exponential **[Sztipanovits, 2001]**

In addressing the problem of dynamic mission planning, hierarchical control will always be required. **[Sztipanovits, 2001]**

Challenges are command and control, sensors, communications, and integration. **[Van Fosson, 2001]**

There are essentially four areas in UGV development that cause the most stress on system design: mobility, communication, power, and navigation. These four areas tend to trade off among each other. For instance, better navigation capability generally means that less communication is required. Larger systems have better mobility, but require more power, etc. The most difficult problem for UGV systems regarding mobility is negative obstacle detection (holes). The shallow look angles tend to obscure detection using visual stereo systems. LIDAR looks to be a promising technology for both negative obstacle detection and probably detection of mines. The Demo III UGV program utilizes a LIDAR system in a "nodding" mode to provide detailed map in front of the vehicle. The DEMO III navigation algorithm then uses this map, along with visual data from stereo EO/IR cameras to plan a route that gives the vehicle the most stable path. In brown water, this solution may not work. Also, in VSW the UUV may have to deal with kelp. Also, an essential element of a robot that runs the risk of being flipped over is a capability to right itself, or a design where it doesn't matter which way is up. This design could simplify deployment by allowing air dropping of systems into the target location. **[Clemons, 2001]**

From the MPRS field experience:

The primary concern to the users was the fact that the prototype system introduced new batteries into what is an already immense variety of batteries that have to be carried into the field. The user community may benefit from agreeing upon a standard family of high-density battery configurations. Other user requests were night vision capability and a lethal robot response capability. **[Bruch et al., 2000]**

The current goals and challenges listed in the descriptions of major DoD robotics programs is instructive for the evident *Lessons Learned*. These goals and challenges

represent perceived disparities between operational requirements and technological capabilities.

4.3.4.1 Challenges Motivating the DARPA SDR Program

Goals and challenges of the DARPA SDR program include the following:

- ✓ A large collection of micro-robots that can move, communicate, and work collectively to achieve a collective goal.
- ✓ Human robot interface technologies that will permit the human to interact with the robots as a group (including the capacity to task and query), rather than requiring the human operator to interact with each and every individual robot.
- ✓ Develop the software needed to enable the cooperative behavior of large numbers of micro-robots to accomplish collective tasks.
- ✓ Develop the software technologies necessary to enable inter-robot communications to support collective behaviors.
- ✓ Develop computational strategies that are compatible with a highly resource constrained environment.
- ✓ Develop human interface strategies that support both tasking and query of the micro-robot collective.
- ✓ Perform experiments to reliably assess the progress toward developing the missing software needed for the successful operation of large numbers of micro-robots. **[Gage, 2001]**

Inferences we may make from the above listed challenges include the following:

- It is difficult to coordinate many small vehicles.
- It is difficult to scale control strategies to very large numbers of vehicles.
- It is difficult to provide useful behavior through cooperative action.
- It is difficult to coordinate multiple robots by multiple operators.
- It is difficult to communicate among co-specifics and among operators due to, among other causes, problems with bandwidth.

From our earlier reports on the underwater environment, we must anticipate that most of the SDR program challenges will be even greater when the agents are operating as UUVs.

4.3.4.2 Challenges Motivating the DARPA MARS Program

Similarly the goals and challenges for the DARPA MARS program are as follows:

- ✓ Develop the software needed to synthesize the desirable features and capabilities of both deliberative and reactive control while incorporating a capacity for learning. This solution must include developing the theory and technology for integrating sensory perception, processing and representations into a single control architecture.
- ✓ Develop the theory and technology necessary to benefit from learning as a means of composing and refining control software for autonomous mobile systems.

- ✓ Develop the theory and technology for symbiotic sensor interaction needed to enhance the perception and support the reasoning required for the real-time control of an autonomous mobile robot in a complex, dynamic, unstructured environment.
- ✓ Develop a uniform set of evaluation criteria needed to evaluate the autonomy quotient (AQ) of an autonomous mobile robot.
- ✓ Perform field experiments and demonstrations to reliably assess the progress toward developing the missing software needed for the successful operation of mobile autonomous robots.
- ✓ A software solution framework that enables autonomous robots to synthesize the desirable features and capabilities of both deliberative (symbol-mediated) and reactive (sensor-mediated) control, while incorporating a capability for learning.
- ✓ A software composition methodology that incorporates both programming (hand coding) and learning-derived (automated coding) software composition to increase the ability of autonomous robots to function in unpredictable environments.
- ✓ Context driven, multi-sensor processing to disambiguate sensor-derived, environmental state information. This capability has the potential to empower the robot to accurately characterize the environment, and hence potentially exceed the performance of a human operator.
- ✓ Metrics and benchmarks to assess and quantify mobile robot autonomy.

The inferences we may draw from this second list are as follows:

- Roboticists do not yet know how to get their products to operate in unpredictable environments.
- Programming appropriate responses to novel tasks and environments is very costly and impracticable for the MCM mission.
- Roboticists do not yet know how to create an efficient and successful learning machine.

4.3.4.3 Challenges Motivating the DARPA TMR Program

The DARPA TMR challenges are as follows:

- ✓ Adequate power (energy);
- ✓ Adequate perception for obstacle avoidance, navigation, mission requirements;
- ✓ Adequate communications to be useful to the soldier/operator;
- ✓ Adequate processing power;
- ✓ Adequate (effective and efficient) operator interface;
- ✓ Adequate mobility. **[Gage, 2000]**

The inference we may draw from the TMR list is as follows:

- Small untethered ground robots are not ready for tactical operations.

4.3.4.4 Challenges Motivating the Demo III Bravo Test

The reported Demo III-Alpha deficiencies were as follows:

- ✓ Target scans were performed vehicle-relative, operators could not make the necessary geolocation transformations.
- ✓ Vehicle had no terrain elevation data.
- ✓ Could not establish a correspondence between scan results and the terrain map at the OCU.
- ✓ No way to adjust the resolution of the RSTA sensors.
- ✓ No ATR-on-the-move capability.
- ✓ Algorithms suffered from a high rate of false alarms.
- ✓ No range information for ATR.
- ✓ No AGC for the FLIR.
- ✓ Detection algorithms were performed serially, wasting time and resources.
- ✓ Communications suffered delays and dropouts. **[Bonner, 2001]**

And from another opinion of Demo III challenges:

- ✓ Major problem is autonomy – involving perception for mobility; specifically for obstacle avoidance of both positive and negative obstacles
- ✓ As this had occupied most of the developers' attentions, not a lot of time and resources are being spent on the RSTA mission **[Haug, 2001]**

The inference we may draw from the Demo III list are as follows:

- ▪ Large semiautomatic ground robots are not ready for tactical operations.

4.3.4.5 Challenges Anticipated by the Army's FCS Program

The expected challenges to the Army's Future Combat Systems objectives:

- ✓ Autonomous (unsupervised) mobility;
- ✓ Tactically intelligent behaviors;
- ✓ Robust adaptive perceptual capabilities;
- ✓ Intelligent, adaptive vehicle behaviors;
- ✓ Modular, non-intrusive soldier-robot interface;
- ✓ Schedule – the above three deficiencies to be addressed in the FCS STO from 2000 to 2005. **[Bornstein et al., 2001]**

The inferences that we may draw from the above list are as follows:

- ▪ FCS has not considered the necessity of evolution.
- ▪ The ambition of FCS is comparable to the creation of man from the Euphrates mud.

4.3.4.6 Summary of the UGV Technology/Capability Shortfalls

- ✓ Critical non-robot-specific component technologies:
- ✓ Power: need higher energy densities.

- ✓ Displays: need more of the relevant information, need to discover what is relevant.
- ✓ Communications: need greater bandwidth, unimpeded though the medium – greater than, but at least equal to non-robotic solutions (i.e. soldier assigned).
- ✓ Processing: need higher MIPS per mass/volume/power.
- ✓ Sensors: need higher resolution, range; lower size, weight, power draw.
- ✓ Localization: need the equivalent of CP-DGPS anywhere w/ or w/out DGPS. **[Gage, 2001]**

Critical Robot Capability Needs:

- ✓ Locomotion: go anywhere.
- ✓ Perception: recognition of obstacles, landmarks, threats, friends.
- ✓ Detection, classification, identification, localization, and tracking of targets.
- ✓ Sensor guided mobility.
- ✓ Being small enough and big enough.
- ✓ Implementation: fitting in rucksack envelope.
- ✓ Achieving functionality, performance.
- ✓ Supervised autonomous navigation.
- ✓ How operator tasks, monitors, overrides.
- ✓ How robots actually execute moves.
- ✓ Implementation: making it all actually work.
- ✓ Robotic system decomposition/architecture(s). **[Gage, 2001]**

Key technologies and issues:

- ✓ Communications - [greater than manned solutions, if man remains in the loop].
- ✓ Power - [equivalent to manned solutions].
- ✓ Perception and mobility.
- ✓ Modularity: minimizes duplication of sensor and processing resources, improves sensor fusion for alarms and alerts.
- ✓ Interoperability: for mechanical, power, and messaging.
- ✓ Integration and implementation: [however] there is a tension between integration flexibility (modularity) and tight subsystem coupling. **[Gage, 2000]**

But our greatest operational/programmatic/technology shortfall is that we have not yet been able to (1) define a useful task for a robot, and (2) get that robot to perform its defined task *reliably and repeatedly on its own in any unpredictable real-word environment*. Thus, we have a very tenuous foundation from which to proceed to more complex capabilities.

4.3.5 Addressing the Challenges

4.3.5.1 Use of a Joint Architecture for all Unmanned Ground Systems

Generally, it is recognized that commonality saves time and money. The reuse of developed components is economical. The adherence to information exchange standards saves the labor of translation.

> The U.S. Army Tank-Automotive & Armaments Command UGV soldier-machine-interface may be of value to UUV applications. Useful also are the hierarchical software architecture (4D/RCS) and JAUGS communication protocols developed by

NIST and the Joint Robotics Program Office, respectively. We also find a lot of value at TARDEC-Vetronics in utilizing software APIs in increase re-use of software developed. **[Brendle, 2001]**

Joint Architecture for Unmanned Ground Systems (JAUGS):

- ✓ objective to ensure interoperability of future unmanned ground systems
- ✓ use will be mandatory on all JRP systems
- ✓ ref: http://www.jointrobotics.com/Jaugs/ **[Gage, 2000]**

There is a risk to the imposition of standards and the reuse of components and architectures that are sub-optimal, however. The risk is the perpetuation of inefficiencies and the inhibition of the development of better solutions. Yet any of the factors that determine the optimality of solutions, including cost, interoperability, extensibility, and efficiency, may be traded in the standardization process.

One category of standardization rules might guide the evolution of information exchange formats so that the degree of compatibility among component versions exists at least as long as the components remain in general use. After all, standards like dictionaries only represent the habits within the participating population—habits that have their own good and common reasons for adoption and persistence.

4.3.5.2 Addressing the Challenges of System Integration

In addition to the *Lessons Learned* from the MDARS program that we mentioned at the beginning of this Section, the DARPA/Army Demo programs, used to quickly integrate various technologies and demonstrate their utility in a tactical unmanned vehicle RSTA scenario, provided many good lessons in systems engineering. Some examples include the following:

A complex system integration effort requires a well functioning IPT. **[Glass, 2001]**

Integrators must pay close attention to the component experts. **[Gothard et al., 2001]**

It is critical to have an up-to-date interface control document (ICD) to facilitate the integration of components provided by different sources. **[Glass, 2001]**

Complete descriptions of interfaces are required for both software and hardware integration **[Gothard et al., 1993]**

Make sure that the component developers comply with the software interface standards. Otherwise, fixing interfaces may consume as much time as writing the component code. **[Gothard et al., 2001]**

The integrating authority should provide a development and debugging environment for the developers. A good simulation of the vehicle would have been useful for independent developers. **[Glass, 2001]**

The ability to record and to playback real or simulated data assists system checkout **[Gothard et al., 1993]**

> When porting software one needs tools and test cases to verify a successful port **[Gothard et al., 1993]**
>
> Do not depend solely on manufacturers' specifications for products. Rather the products must be characterized in the environment in which they will be used. **[Gothard et al., 1993]**
>
> The computing hardware and operating system baselines should be stable before effort is expended to integrate applications. **[Glass, 2001]**
>
> When developing new software, make sure that the supporting hardware is absolutely reliable. Having hardware teams on standby helped. **[Gothard et al., 2001]**
>
> Plan alternatives for high-risk items. **[Glass, 2001]**
>
> Have a backup plan for everything. When expecting a new piece of hardware, or a new software solution for a task, keep the older working version around (including interfaces) just in case the new version does not integrate well and function as planned, or does not arrive in time. **[Gothard et al., 2001]**
>
> Integrators must keep exact records of steps taken during integration, debugging, and troubleshooting. Changes can take the system away from functionality, and restoration will be difficult without records that detail the working states that were passed through. Records of failure states are also helpful for making later design improvements. **[Gothard et al., 2001]**

Occasionally, failure states turn out to be serendipitous when the real error was in our expectation of how the system should work. The lesson is that a complex system can be characterized by state variables or parameters, but the functionality of those individual states cannot be known with certainty until the environment in which the function must be exercised or expressed is also equally characterized. No one state of the system should be expected to be universally useful.

4.3.5.3 Golden Rule of Evolutionary Development

> When debugging, make only one change at a time. **[Gothard et al., 2001]**

4.3.5.4 Making Sense out of an Uncertain World

Active perception is the means used by advanced animals to make sense out of the uncertain world. Robots can be programmed without too much difficulty to perform similarly. Active perception begins with the awareness of uncertainty. A behavioristic definition of *uncertainty* is the inability to choose, evidenced by an inhibition of motion when movement would ordinarily be expected (from the observer's perspective). An expectation emerges to overcome the inhibition. An *expectation* may be defined as an orienting response to the location of a previously detected environmental feature. The particular feature selected depends upon the prevailing biases. Should the feature exist at that location, then the expectation is confirmed, at which point, the organism improves its recognition. The

successful confirmation evokes a second expectation, based upon previously learned sensor–sensor and sensor–motor relationships, that lead to a second orienting response, and, if confirmed by environmental conditions, further improves the recognition. Complex behaviors can be rapidly and smoothly executed following this sequence. However, when an expectation is not confirmed, the level of uncertainty is increased, the sequence is interrupted, the prevailing biases are reset (permitting alternative choices), and the organism is forced to start over with a new expectation.

Under uncertainty, it is necessary to create hypotheses, which are nothing more than complex expectations. Without uncertainty, no hypotheses would be created. This ability to deal with uncertainty permits the organism to expect different features from the environment and test them out through some active exploration. Recognition, certainty, or confidence validate one's hypothesis with the sensor data that were actively acquired because the hypothesis was created and the required features were present within the environment. Errors of validation, which can occur when some of the inhibitory neural mechanisms are dysfunctional, are called hallucinations. Dreams are hallucinations as the process runs free without the benefit of environmental feedback.

Thus, natural vision systems accomplish much more than the simple extraction of features from the input stream. Put another way, the extraction of features in natural systems is more involved than template matching. Natural vision is a component of a larger complex of systems that meet the information needs of the organism. The natural vision system independently acquires information to achieve the organism's objectives under uncertainty. Uncertainty exists because the environment is chaotic. The reduction in uncertainty is accomplished by the agent's mobility through the environment. This operation increases uncertainty for a third party, in accordance with the second law of thermodynamics, but decreases uncertainty for the agent. Active perception is a form of mobility where the direction of movement is determined by an interaction of expectation and results. The new information is used to resolve the uncertainty.

The integration of sensory and motor capabilities increases the local computing difficulty many times over compared to an application that uses only sensors or effectors, supplementing the missing capabilities with human cooperation. The difficulty resides in the requirement to adjust effector output as sensor input changes, and in the consequences on sensor input as effector output changes. Even a stable world can produce a huge variety of appearances as an agent moves through it. This complexity is, of course, compounded because the world is also dynamic and unpredictable, full of surprises, and occupied by other actively perceiving agents.

Biological perception is active, with information making several round-trips between the creation of expectations and their validation through sensing selected environmental features before gross higher risk behaviors are released and the organism commits itself. Active perception with the consequent buildup of certainty (familiarity) is the means by which natural intelligence deals with uncertainties in the operational environment. The incorporation of active perception mechanisms into robot control algorithms should provide similar advantages.

4.3.5.5 Use of Adaptation or Learning

Programming the rules that permit a robot to operate in an unstructured (unconstrained) environment is very difficult and has been the unsuccessful approach of Expert Systems in artificial intelligence (AI). Therefore, learning algorithms are now favored.

> Learning algorithms will be necessary to insure robustness and the ability to rapidly adapt to new environments and conditions. **[Bornstein et al., 2001]**

There are other benefits to learning. One benefit is adaptation to component failure—contributing a solution to our requirement for fault tolerance.

A notable example of this application is an Air Force Office of Scientific Research-sponsored product from Barron Associates, Inc.

> They report that their self-designing control system can continuously optimize performance and can accommodate events such as failures, anomalies, and damage, as well as maximize an aircraft's flight envelope, maneuverability, and changing mission requirements. It could provide compensation for damaged or malfunctioning control surfaces. The self-designing controller would automatically determine the effects of a collision, equipment failure, mid-air explosion, ice formation, or other event, and use the remaining control surfaces to adapt to these effects and maintain safe flight. **[Jacobs, 1996]**

While roboticists are actively experimenting with adaptive algorithms that provide perceptual capabilities for mobile robots, and create environmental maps, they will sometimes need adaptive algorithms that permit the robot to function even when its sensors or effectors have been damaged or misaligned.

Is this form of adaptation always a good thing?

> The MDARS-I developers noticed that a well implemented adaptive behavior could mask component faults such as a problem in the steering mechanism that constantly "pulled to the left". **[Gage, 2000]**

But, can we fault a system that continues to perform even as components begin to fail?

> A combination of adaptive compensation and fault detection and reporting would be desired to ensure graceful degradation without masking the evolving failure. **[Everett, 2001]**

Indeed, nature employs such mechanisms to permit the preservation of most functional capabilities under conditions of injury and aging. The existence of considerable reserve, redundancy, and reallocation ability facilitates these mechanisms, while the ubiquitous distribution of pain fibers provides for the early warning of conditions internal and external to the organism to which it should take some prophylactic or defensive action.

A robot must also adapt to the new task objectives, and to short- and long-term changes in its capabilities, and in the demands of the workspace. Autonomous work systems must therefore have the capacity for continuous learning and adaptation.

Old learning should facilitate new learning. The hope of every teacher is that with each new lesson, learning is a little easier than the last. Building on previous knowledge makes new learning possible., Allowing previous knowledge to bias new responses makes new learning possible. A robot should not have to be re-taught the use of a wrench or the purpose of nuts and bolts for each new assembly project.

Training time in natural adaptive systems is proportional to task complexity. We should anticipate that as task requirements increase, so should the cost of training an autonomous work system in preparation for task performance. Systems must be engineered to minimize this cost. Thus, learning should be preserved so that generalizations to new tasks become possible.

The development of learning algorithms for robotics applications could benefit from a clearer understanding of learning theory from the neuropsychological literature. Unfortunately, the AI community that supports robotics development has ignored this literature. The problem of reliability or certainty in control may explain this oversight. Robots are still thought of as machines, of which the performance must be absolutely predictable. Learning, in the biological context, introduces an element of uncertainty that has been at best a nuisance in robotics applications.

Biological systems are also machines, and more importantly, they are machines that make errors. Learning and adaptation permit biological machines to recover from errors, and in some cases, to discover the benefits of making what was previously an error, but after learning, becomes a more successful response.

4.3.5.6 Redefining Machine Intelligence Requirements

A problem with the development of machine intelligence is that humans (robotics developers) do not understand their own cognitive mechanisms. This lack of understanding would not be a problem if the developers did not attempt to recreate strictly human capabilities. For example, humans use maps to maintain their orientation with respect to fixed features in the environment. Robot developers assume that this type of orientation is also required for a robot and, therefore, the robot must have a map or create a map from the integration of its sensor experiences. An alternative approach might be to ask what information the robot must have to accomplish the task assigned by the human operator. The laying down and subsequent retracing of trails is one possible substitute for a map.

Approaches taken by the developers of the TMR and Demo programs to meet the many challenges listed above show the common human-centricity of the development process. These approaches consciously or unconsciously interpose between all sensor information-processing algorithms and all execution commands for navigation and target acquisition the requirement to make the information intelligible to a human observer. Because of this requirement, the common approach to machine recognition involved template matching of an image that was first identifiable to the human operator.

Similarly, obstacle avoidance involved terrain characterization of environmental elements (scene components) into broad classes (such as soil, green vegetation, rocks, and man-made obstacles) that were assumed by the developers to have an impact upon the mobility or operation of an autonomous system. They do have an impact upon the mobility of a human organism, and upon the mobility of vehicles driven by humans such as HMMWVs, but it might be imposing an unnecessary constraint upon the information processing necessary for some other type of autonomous agent to first view the scene and the problems of mobility through the perceptual requirements of a human. Does the bull in the proverbial china shop care if the shelves are loaded with delicate porcelain? Probably not, the bull no doubt only cares that the obstacles are negotiable in his objective to exit the shop. Knowing the nature of bulls, we do not generally place them in china shops, but we do find other good uses for them.

Taking a lesson from this example, to develop a successful and useful autonomous underwater vehicle, we may not require the onboard information-processing algorithms to comply with our perceptual and decision-making needs. Instead, and more simply, we could determine the full scope of information available in the task environment, and the impediments and assistances available in that same environment. Then we could define the behavioral objectives appropriate for a AUV, given an available set of sensor and motor capabilities, and then work out the necessary information-processing steps that most efficiently achieve the required behaviors with the available equipment under the particular task circumstances and task objectives.

4.3.5.7 Redefining Machine Autonomy

4.3.5.7.1 Defining Autonomy

What is autonomy? Are people autonomous? Are dolphins? Are dogs? Can a machine be autonomous? How is an autonomous machine supposed to behave? We can probably approach these questions from several different perspectives, but we are interested here in understanding the mechanisms of autonomy so that we can emulate these mechanisms in a robot. Therefore, we ask what an organism is doing when it demonstrates autonomy.

For man, autonomy is customarily considered to be a result of free choice. Webster's Dictionary defines autonomy as the quality or state of being self-governing. An autonomous person is one who is allowed to act on his/her choices. A dog, on the other hand, is generally not given this liberty, perhaps for the reason that the dog is not considered to have the capacity for free choice. However, those who have attempted to maintain control may be forced to concede that the dog indeed exercises free choice. A dog does what it likes, and those who wish to control a dog find that their success is greater if they can couple their desired result with something that the dog likes to do.

But why stop with the dog? Is a bird autonomous? How about a frog, a fish, a lobster, or a roundworm? On close inspection, all of these species seem to have choices, and often make the right choice for their circumstances. They find the proper food, the proper mates, avoid predators, and survive. Therefore, we have equated autonomy with survival.

Even a single-celled protozoan survives without outside control. First of all, the protozoa exist in large numbers. The loss of any one or even many of them does not immediately

threaten the survival of the species. Even so, each protozoan has built, within its cellular apparatus, mechanisms to preserve its integrity. These mechanisms allow it also to recognize and acquire food, avoid predators and poisons, and find co-specifics for copulation. Since the protozoan is unicellular, its behavioral mechanisms must function at sub-cellular levels. Protozoan mouths, swimmers, eyespots, and chemosensors are all elaborated from the cell membrane—an organism in detail within a single cell! This differentiation of the cell structure contributes to variety in function, and variety in function to survival.

We can reduce the causal chain of autonomy mechanisms even further to the properties of DNA, as can be done with all vital mechanisms. We might venture to propose that autonomy is a fundamental property of DNA. The ability of DNA to manufacture proteins or enzymes, and regulate their action, must subserve all autonomy as these are the substrates of the cytoplasm and the differentiation of cellular components that lead to specific sensitivities to the environment, and to the reactive capacity of the cell.

What does the DNA molecule do to promote its own survival and replicate itself? The replication of DNA is well known. Under the circumstances in which most DNA is usually found, that is, protected within the cytoplasm of a cell, the DNA, through its control over the architecture and function of the cell, directly attempts to preserve itself. Yet, even outside a cell, the DNA survives. The simplest configuration in which DNA is found is the virus. The viral DNA manages a protective coat of protein before it leaves its host cell.

The DNA molecule also can exemplify the mechanisms of autonomy. Each nucleotide on the DNA strand is a receptor for another specific nucleotide on another DNA strand or on a mRNA strand. Once the sites on a strand are all occupied, the molecule unzips and it is ready for replication. The DNA, through mRNA and tRNA also determine the selection and sequencing of specific amino acids from the intracellular environment to assemble proteins. Some proteins hang around the DNA and act as enzymes. *Molecular forces, intrinsic to the DNA and to enzymes that it produces, regulate this process and subserve the binding and unbinding of different connections that rebuild the molecule and then split it apart to repeat the process.* The availability of critical amino acids limits the rate of this process. *Thus, the DNA and mRNA strands can be viewed as a sequence of receptors that wait for the occurrence of a particular environmental event (the presence of a tRNA molecule with a bound amino acid).* Yet the DNA also causes events to occur that increase the probability that critical amino acids will become available to it. The power that the DNA molecule has to control its environment is exercised again through the production of proteins. The completed protein, by virtue of its specific conformation, moves off the mitochondrial factory to become incorporated into the cellular architecture or act as an enzyme to further affect some cellular process. The DNA is thus capable of regulating cellular function according to its requirements for survival and replication.

The essential elements of an autonomous mechanism are all present in processes controlled by or intrinsic to the DNA, and all contribute to the persistence (survival) and replication of the DNA. These essential elements are as follows:

- Intrinsic physical forces that attract or repel components (motive forces).
- Receptors sensitive to specific environmental conditions (discrimination or selectivity).

- Mechanisms to limit the environmental effects on the conformation or composition of the agent (encapsulation).
- Mechanisms to alter the physical relationship of the agent to its environment (mobility).

An autonomous system survives. Whatever promotes survival thus determines autonomy. This definition of autonomy is consistent with the biological perspective that autonomy is a requisite for survival, for survival is synonymous with the ability to act again. In a single-celled organism, the differentiation of the cell membrane promotes survival by forming a connection between an environmentally sensitive region and an effector region that moves the cell relative to the environmental stimulus. This connection has the qualities of a reflex. A reflex, however, is not what is customarily thought of as a certain and invariant reaction given the proper trigger conditions. Rather, the reflex is a non-linear response to a trigger stimulus that is much modulated by the internal conditions of the organism. The reflex response is calculated to maintain the optimal internal state of the organism, thus promoting survival under the prevailing environmental (stimulus) conditions.

The protozoan lives by its reflexes, envaginating nutrients, avoiding toxins, and occasionally communicating nuclear information with friends. Without risk of over generalizing, the role of these reflexes may be extended to all living organisms, including man. In multicellular organisms such as man, reflexes subserve all behavior. To get a rich variety of behaviors, one must evoke and modulate many reflexes. Natural controllers (brains) control by virtue of their ability to evoke and modulate the reflexes. All natural behavior is accomplished through the evocation and modulation of reflexes. All high-level adaptive behavior is accomplished through the conditioning of these reflexes, which are always coupled to environmental conditions.

Natural selection has ensured that most reflexes are very useful, meaning that the stimulus categories are quite relevant, so the responses achieve reliable and beneficial results. We use reflexes to orient to biologically significant events. We also use reflexes to avoid other biologically significant events. Without these reflexes we would not survive long, and there goes our autonomy. If our reflexes are well designed, all of our responses will be appropriate in the sense that they promote our survival. Problems do come up when the survival of different individuals conflict, or when the environmental conditions change beyond the limits in which the fundamental reflexes were designed to operate. In the former case, one of the two individuals may disappear. In the latter case, an entire species may become extinct, but fortunately for us, there is more to the reflex story. Higher-level processes permit the organism to use its reflexes to effect the necessary changes in the environment that restore the viable conditions.

Before we continue the story, it might be useful to contrast an automatic process (that is the common perception of a reflex) with an autonomous process (that is subserved by biological reflexes). An automatic process executes an action without a second-order modulator. External or internal events, with respect to the host system, may trigger, generate, or regulate an automatic process, but do so without regard to the consequences upon the host. The thermostatic control of a heater is one example. While the process could maintain a reasonably constant temperature in the medium connected to the thermostat, the process is inflexible with regard to the set-point of the temperature, which must be adjusted by some other means (a human operator?).

A different example of an automatic process is a wind-up toy. The tension on the wound spring of the toy acts as internal trigger and driver (source of energy) to activate levers and turn gears that animate the toy. The mechanical links to the external environment are strictly deterministic and yield a fixed behavior until the spring loses its tension. Typical wind-up toys do not have sensors of the external environment to modulate the links between spring and mechanical effectors, thus they are likely to bump into obstacles and fall off ledges. These two examples demonstrate the inadequacies of automatic processes. In the first example, the automatic process was deterministically dependent upon the conditions in the external environment, while in the second example, the automatic process was deterministically dependent upon conditions in the internal environment.

An autonomous system is necessarily built with automatic elements, that is, with receptors, sources of motive energy, and mechanical effectors. In addition to these, the autonomous system has sensors for the internal and the external environments that provide information used to modulate the automatic processes. While the automatic process responds unidimensionally to either internal or external factors, the autonomous process integrates internal and external factors in the response decision. An example of an autonomous process is the patellar tendon reflex in a biological system. Muscle tension is maintained by internal factors (primarily spinal and cortical influences on the motor neuron) but modulated by the change in the stretch on the tendon brought about by an external load on the limb that changes the joint position and stretches the muscle. The reflex counters the changes in joint position by activating an opposing muscle group. The ideal position for the system is at the center of its response curve, the point of maximum slope. The reflex to restore the system to the ideal position opposes perturbations from the environment.

The advantage of an autonomous process over an automatic process is that action in the former leads to an improved status of the system in relationship to the environment and thus to a reduction in the required intensity of subsequent action. The action of an autonomous system is dependent upon internal and external factors. The autonomous system, by being self-governing, optimizes its own position with respect to what is possible. Furthermore, the extension of the basic mechanisms of autonomy with long-term adaptation allows an advanced system to predict changes in the environment and act in anticipation of environmental events, thus freeing the system from a strictly reactive mode of operation. (Short-term adaptation of reflexes does occur at the level of the spinal cord, but long-term adaptation (learning) does not occur there. Learning requires an association ganglion (brain), but even round worms have them.)

4.3.5.7.2 Requirements for Autonomous Behavior

We now return to our statement that reflexes afford changes in the external environment.

When the external environment changes, the potential for information increases. In the simplest sense, autonomy is evident in an agent's ability to act on information that has become available as a consequence of some change in the environment. The change in the environment may be initially independent of the action of the organism, but at some point, the reflexive organism responds and contributes to that change. The direction and magnitude of the change is determined by the evoked reflex, which is dependent upon the internal needs of the organism and the external circumstances. Because the environment generally changes

slowly relative to an animate organism, much of the new information will be due to changes induced by actions of the agent.

An autonomous system must independently acquire information to achieve an objective under uncertainty. For example, the protozoan is uncertain about the location of food or a co-specific. The protozoan reduces uncertainty by its mobility through the environment, for the consequent changes increase its information. To use information, the autonomous agent must have sensors for its need (analogous to the motive force for DNA), sensors for its environment (analogous to the selective sensitivities of DNA), and a means to encounter and acquire the needed information (the mobility of proteins produced by DNA). As we have tacitly assumed that an agent has coherent boundaries, these three other requirements constitute the basis for autonomous behavior.

An autonomous robot will also encounter uncertainty. This uncertainty should be anticipated by mission planners because of the many possibilities for surprise in the task environments, including an element of randomness inherent in the robot's control processes and dynamics. Additionally, in a working system, the operation of the robot will continually modify the appearance of the environment, either by disturbing the lay of the objects or by changing the robot's viewpoint. The autonomous robot, by predicting these changes, should be able to control the increase in entropy due to its own activity and avoid disorientation. An automatic robot would not be so prepared.

4.3.5.7.3 Adaptation Mechanisms: Assimilation and Accommodation

Autonomous behavior involves three components: (1) self-generation of activity, (2) self-suppression of activity, and (3) self-testing of results. The organism must have control over its own on-off switch, that is, modulate its own level of activation, and it must determine when its actions have achieved its goals. As the environment changes, presenting new information to the organism, it must alter its response to survive. The act of response modulation is called adaptation.

Animals have two mechanisms of adaptation. The first is accommodation, which involves adjustments of the internal environment. The second is assimilation, which involves motoric actions on the external environment. The regulation of blood glucose is an example of accommodation, while eating is an example of assimilation. The objective of adaptation is survival, but more specifically, the maintenance of the optimal state for survival, which we call homeostasis. Assimilation mechanisms are usually brought to play when accommodation mechanisms have reached their homeostatic limits. This definition of adaptation follows from observations that agents must be able to adjust internal conditions and operate on the environment to survive. Each mechanism involves the play of automatic processes. Accommodation uses reflexive modulation of automatic processes to adjust the internal environment, while assimilation uses the reflexive modulation of automatic processes to make adjustments to the external environment.

4.3.5.7.4 Providing for Robot Autonomy

The biological mechanisms represent real working examples of autonomous systems, the behavioral capabilities of which we would like to achieve in an unmanned system. We may avoid the pitfalls inherent in the application of models of cognition that are characteristic of

most contemporary robotics control algorithms by adhering closely to the biological mechanisms.

We attempt to emulate the biological mechanisms of autonomy because something is known on how they work. We can borrow from this literature. The autonomous machines are intended to assume many tasks currently performed by man, in man's work space, and using man's tools and symbols. A machine that is anthropomorphic in hardware and software may most easily be inserted into those tasks.

While the initial implementation of analogous mechanisms may not produce the most impressive behaviors, we assert that they will be required for the development of more robust and adaptive behaviors.

Generally, traditional AI approaches to unmanned systems capitalize on constraints in the operational environment, e.g., an un-patterned floor with downward looking cameras—looking for the appearance of the line demarking the boundary between wall and floor. Nature also takes advantage of such constraints. The common housefly observes the open sky with eyes located on top of its head for small, dark, moving targets. Houseflies are quite successful, but are easily confused in visually complex environments, and are not very useful to man. However, there are rather mundane tasks, such as foraging, that can be performed by simple biological systems such as the garden slug, that might also be efficiently and usefully accomplished by robots using similar mechanisms.

The perceptual capabilities of a garden slug are proportional to its judgment capabilities and to its behavioral capabilities. This general law of functional proportionality is sustained at all levels of the phylogenetic scale, including man. *A necessary conclusion from this law is that the perceptual capabilities of man are going to be reproduced in an artificial visual system only after provisions have been made as well for the judgment and behavioral capabilities.*

To achieve autonomy in a robot, the robot's design must ensure that the top behavioral priority for the robot is to survive. We should be able to structure the task situation so that the robot works to survive and views our own survival as critical to its own (like a loyal dog). In this way, the robot will be autonomous and useful.

At this point, we may ask what are the necessary reflexes that promote survival in a robot? Surely they will be similar to our own. The robot needs to preserve its physical integrity, it needs to maintain an adequate energy reserve, it needs to maintain a stable and consistent orientation to the environment and to maintain freedom of movement. Involved in these protections are reflexes for obstacle avoidance, avoidance of extremes in temperature, pressure, vibration, chemicals and other irritants; reflexes to orient to specific sources of energy and reflexes to consume them; and reflexes to orient to gravity or the skyline or some other fixed feature of the operational environment. Recall that these reflexes will control behavior in proportion to their degree of importance in maintaining survival at the moment. For example, orientation to the environment should take precedence over the consumption of an energy source, yet when energy reserves are low, consumption should proceed even under exposure to noxious chemicals, pressure, or temperature, but still should be interrupted by an impending collision with a massive object. With these reflexes alone, a robot could be expected to survive in a temperate climate. It might even perform some well-defined task

with great reliability if the task was tied to its reflex processes. We may be disappointed, however, if the task would unexpectedly change in some way, for we could not easily adapt the robot to different environments.

The way nature has handled this problem is to permit insignificant environmental events (those that have initially little survival relevance) to become associated with those environmental events that have great survival relevance. For example, if a robot finds an energy source consistently in a certain place, then returning to that place would increase the probability of again encountering the energy source, even if none was currently present. Returning later, or just waiting around may pay off if the energy source is intermittently present. To accomplish this, the robot needs to be able to recognize some feature of the environment in addition to the energy source and be able to attach some special significance to that new feature. A simple mechanism is to have the new feature

trigger the same orienting and approach reflex as the energy source that was found in its vicinity. The biological mechanism for this process is known as classical conditioning. It has been well-described in the biological literature and can be implemented in hardware and/or software, as many have shown. We have noted that learning, of which classical and instrumental conditioning are variants, depends upon the presence of an association ganglion or brain. There is a huge literature on the architecture of brains and the processes that contribute to the various types of learning that can be used by the robot developer to accomplish analogous processes for his or her robots.

Once the new features have assumed through learning some survival importance for the robot, they too can be used to condition additional features that increase the robot's probability of staying intact, or remaining energized, when the environment becomes less certain. One's entire human endeavor can be connected to a few remote, but compelling reflexes, some of which may be unfulfilled even from early childhood. But, at least in our robots, if we educate them correctly, we may not need to hear such complaints.

5. Summary of the Top 10 Issues

This section summarizes 10 issues that emerged from the compilation of the many lessons learned above. We provide three issues in the area of Operations, three in the area of Programmatics, and four in the area of Technologies.

The reader may rightly wonder how we derived and selected the top 10 issues from the many *Lessons Learned* presented in this compilation. Since we depended upon the sampled community of experts for our basic input, we could have used a voting method and identified the top lessons based upon the largest number of occurrences. Surely, the frequency of occurrence might indicate that the problems that generated the particular lesson came up again and again. It also might indicate that the frequently cited lesson was a hard one to learn. We trust, however, in the superior experience of our sample, and therefore attribute the frequency of the lesson to the commonality of an underlying problem. Where possible, we determined the causes of those problems and developed them as issues.

However, not all of the *Lessons Learned* were clearly associated by their authors, through the problem definition, with a fundamental cause. This uncertainty created an opportunity for us to look independently into the situation, and suggest causes or errors, either in concept or in approach, that might account for some of the more intractable problems. We were thus able to derive additional issues from this editorial assessment. We believe that these issues, while associated with the many *Lessons Learned*, deserve greater attention in the robotics community. These issues probably do not attract universal agreement, rather they represent an alternative view of the situation. As a counterpoint, our issues may stimulate dialogue essential to the discovery of new solutions to the persistent problems that are evident herein.

If the reader is dissatisfied with our listing of the top 10 issues, then we invite the reader to return to the many other *Lessons Learned* presented herein for more relevant choices. We acknowledge that the most important lessons to be learned for any one reader would be those lessons that contribute most to the success of his or her project. Finally, we admit that there are probably many valuable *Lessons Learned* that did not make it into our compilation. We can only apologize for our omissions, and advise the reader to be on the lookout for these unrecorded lessons.

5.1 OPERATIONS

5.1.1 Uncertainty Promotes Survival

There are many corollaries of this truism. The most recent, from the Army's Future Combat Systems concept, is that mobility and maneuverability are essential tactical capabilities. The fundamental advantage of mobility and maneuverability is in the consequential reduction in predictability that it affords, for an adversary that is uncertain of our next move cannot prepare an appropriate countermove. A second corollary is that automatic processes do not promote survival. Automatic processes are very deterministic, and fail to adapt to the challenges of complex environments.

Uncertainty also promotes perception. An indeterministic controller (based on fuzzy logic and bi-directional mapping) is uncertain to itself as well as to observers, permitting the

construction of internal hypotheses or expectations. These hypotheses drive behavior. Self-certainty is improved, without sacrifice to survivability, through the processes of prediction precedent to—and validation consequent to self-generated behavior.

Whether robots are used in logistical support, in RSTA support, or in tactical force projection, they must be survivable, and to survive, they must demonstrate and deal with uncertainty.

Operators, however, prefer to be able to accurately predict and control the behavior of their robots. While this provides advantages for safe—if limited—operation among friendly forces, predictability has definite disadvantages for operation in unpredictable environments. This disadvantage is due to the inherent cognitive and perceptual limitations of a deterministic system and to the opportunistic activities of hostile forces. Predictable behavior is thus not conducive to survival. A degree of uncertainty must be inherent in robot controllers for those robots to be successfully used in real-world environments, including tactical operations.

5.1.2 Many Simple Cooperating Agents are Superior to One Complex Agent

The superiority of large numbers has always been valid in military affairs. It is based on inviolable physical principles. It applies to natural organisms, and will apply to robotics as well. The downside to the use of large numbers of robots in the military context is in the difficulty of control. Operators will be wary of such agents when control is a question. New operational doctrine will likely be required to accommodate many robot agents in a tactical environment.

A single complex agent is limited in time and space. It is appropriately tasked only to a single—if complex—mission. It cannot be sacrificed without great cost. But, it is inherently a technological Goliath that can be disabled through any number of system vulnerabilities. On the other hand, in artificial systems, unit reliability and cost are inverse functions of complexity. Multiple agents permit parallel distribution, and afford great flexibility in deployment. Simple agents are easier to design, produce, use, and maintain.

The problem is that effective processes that promote cooperation among many simple agents engaged in tasks relevant to MCM operations have yet to emerge from robotics research, even though there has been considerable attention in the robotics community focussed on this problem. During the development of the VSW UUV MCM concept of operations, R&D funds should be allocated to explore the possibilities for cooperative behaviors in the VSW environment. There is thus a high program risk to the early dependence upon multi-agent coordination for prosecution of the VSW MCM task.

5.1.3 New Technology Forces Changes in Operations

The military community tends to view technology as an enabler of operations, but history has demonstrated repeatedly that new technology is a transformer of military operations. As every new introduction of technology into the military context forces changes in operations, it is preferred to force those changes upon our adversaries, and be the first ones to adapt to them. Thus, the MCM program office must remain alert to the opportunities for change in

operations that would be permitted and required by the introductions of different robotic technologies.

History has also shown that technologies are extremely difficult to control. Nearly every technology that could be applied to improve the unmanned detection, classification, and neutralization of mines in shallow water, very shallow water, and SZ, could as easily be applied to improve the effectiveness of mines themselves in the objective to detect, classify, and attack targets, and to avoid detection and neutralization in turn during MCM operations. The MCM program office must also consider the potential evolutionary paths of mine and MCM technologies and operations as it pursues its solutions.

5.2 PROGRAMMATICS

5.2.1 Understanding between the User and the Developer is Critical

Successful programmatic decisions cannot be made without the program office/developer and the user acquiring a comprehensive understanding of each other's constraints, capabilities, and expectations. The user has come to the program office with a problem because his old methods of operation, supported by old technology solutions, no longer work. The user is trained in the old methods, and user experience shapes one’s perception of what is possible. To accomplish a new solution, the developer must understand the application, and the user must understand the proposed solution, and adjust methods of operation accordingly. The primary risk of misunderstanding is a product that is at best useless.

5.2.2 Understanding the Technology is Cost-Effective

Successful programmatic decisions cannot be made without a comprehensive understanding of the supporting technologies. The MCM program office must maintain a continuous survey of the emerging technological capabilities in all areas of relevance to the MCM problem. This knowledge will facilitate long-range planning and avoid dead-end products.

5.2.3 Simpler Solutions Provide Better Foundations

A simple solution, however, does not mean a solution that has already been demonstrated. Our definition of a simple solution is that process that meets a few of the requirements without sacrificing or violating any of the other requirements applicable to the system of which the subject solution is a component. By contrast, a complicated solution is that process that meets some of the requirements, while integrating badly with more traditional solutions to the remaining requirements. To the degree that requirements are independent, several simple solutions may be found to the set of requirements. One or more simple solutions may be viable, even though not all of the requirements may have been satisfied in the subject solutions.

To deal with the remaining requirements, the MCM program office should look to those simple solutions that have the highest probability of extension, that is, that can be built upon. Requirements may be added to the solution only as long as the principle of simplicity is maintained. Natural selection in evolution is the model for this process.

5.3 TECHNOLOGIES

5.3.1 Integration Is Not Easy

When humans address a problem, they use tools, some ancient, some new, that experience has proven useful. These tools may include new transducers of environmental emissions such as an IR camera, as well as force multipliers such as a lever, or force reducers as appropriate to permit us to manipulate objects at different scales. The integration of these tools with our own innate capabilities is accomplished anew each time that we take the tool in hand. Learning, or long-term adaptation, does play a role, but what is learned is the refined control of the innate capability. Each new tool is used through an existing skill base.

When we attempt to provide similar tools to a robot, we face two difficulties: (1) the robot has little if any innate capability, and (2) the robot has no capacity to adapt to the new tool. Thus, the robot is redesigned with each addition of a tool. This redesign is the fundamental problem of integration. The difficulties of integration would be minimized if the robot employed an existing interface to use new tools, and if the robot could cooperate through adaptations of its control algorithms. These adaptations are a proven method of vertical (hierarchical) integration.

The MCM program office should encourage the selection or development of core capabilities in a robotic agent. These core capabilities should be task independent, adaptive, and therefore of general utility. The core capabilities should then facilitate the incorporation of unique tools designed to address the special circumstances of the MCM tasks and environment. There is a significant program cost risk in pursuing solutions that do not integrate vertically.

5.3.2 Communications Are Not Dependable

Communications, even under the best of transmission and reception circumstances, can not be relied upon to synchronize information and understanding. When either the transmission or reception of signals fail, even poor communication is impossible. Humans get by with very low bandwidth communications for this reason. Similarly, the most useful robots will demand the least from humans during task performance. Autonomy will be necessary to permit the low levels of communications that will be available. The MCM program office should explore technology and operational solutions that avoid heavy communication requirements. There is a significant operational risk in a dependence upon communications, including satellite communications that serve GPS.

5.3.3 Automaticity Is Not Autonomy

Implementing automatic processes on a robot can reduce the decision-making requirements of the human operator, but risk functional failure when the control algorithms that govern the automatic processes have not been designed for the prevailing conditions that either generate or require a response.

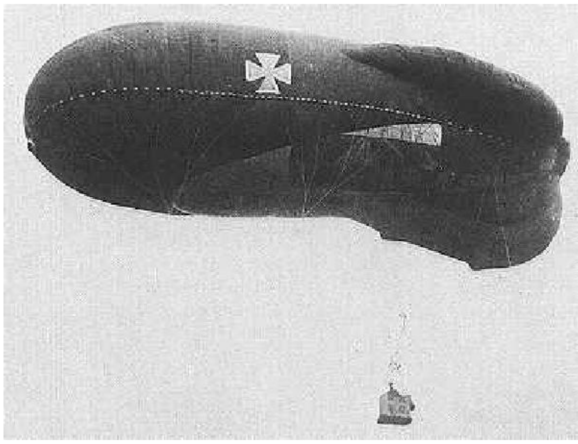

Figure 15. WWI observation balloon.

> The observation balloon is an example of an automatic process (even though a human observer rode along as a passenger in the suspended basket) as it used *passive lift* in order to gain altitude. The observer had little control over the flight trajectory of the balloon, and as a consequence, usually tethered it to a point on the ground.

Autonomy is not a mysterious life force that will spontaneously arise in our robots when we provide them with sufficient sensors and computational resources. *Autonomy results from the self-modulation of responses that impact conditions in the internal and external environments, based upon the confluence of factors prevailing in both, following rules that promote the integrity and well-being of the agent.* Thus, the basis for robot autonomy could be satisfied with the provision of very few processes. The criterion for successful autonomy is survival. If survival is not a required mission or task objective of the robot, then its processes, while automatic, will not be autonomous, and the robot will likely fail as soon as the operating conditions deviate from the designed range of its automatic mechanisms, or whenever they become irrelevant to the integrity of the robot. The MCM program office should encourage the development of fundamental autonomous capabilities in the first and lowest level of technological solutions. This development will establish the necessary basis for the evolution of systems capable of dealing adaptively and appropriately with more complex and unpredictable environments.

Figure 16. WWI biplane.

> The biplane, due to its use of active lift, exemplifies an autonomous process and the difference between automaticity and autonomy. Autonomy optimizes control, and contributes an element of unpredictability that promotes survival. Observation balloons were frequent targets of biplanes during the First World War.

5.3.4 The Road from Teleoperation to Autonomy Does Not Exist

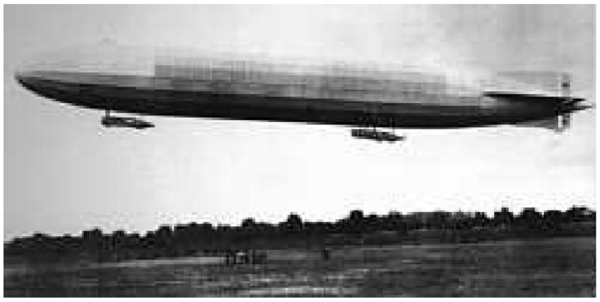

Figure 17. WWI dirigible.

> Even though the balloons of the first World War were developed into rigid motorized airships, armed with machine guns and bombs, they still depended upon passive lift and were limited in control and maneuverability. For the objectives of aviation, passive lift did not take us to the modern airplane.

The road from teleoperation to automaticity probably does exist, but automaticity is not autonomy, as a balloon is not an airplane. The mechanisms of autonomy are fundamental and are re-expressed at all higher levels of the control architecture of an autonomous system. They are bypassed only in pathology and disease.

The adherence to human control over robot operation could impede progress toward achieving robot autonomy. If humans remain in the UGV control loop, then inadequacies in our robot control algorithms will be masked, and we will not be developing the necessary

autonomous foundations for the higher-level perceptual and cognitive processes that we desire in machine intelligence.

We should not attempt to follow a roadmap from teleoperation through semiautonomous to autonomous capabilities, for that road does not exist in reality. Rather we should develop capabilities of fully autonomous, though behaviorally simple, robots from the onset, following the principles of autonomy outlined herein. But to do this, we must start with the simplest of tasks and add task and behavioral complexity only to the degree that autonomy is not compromised.

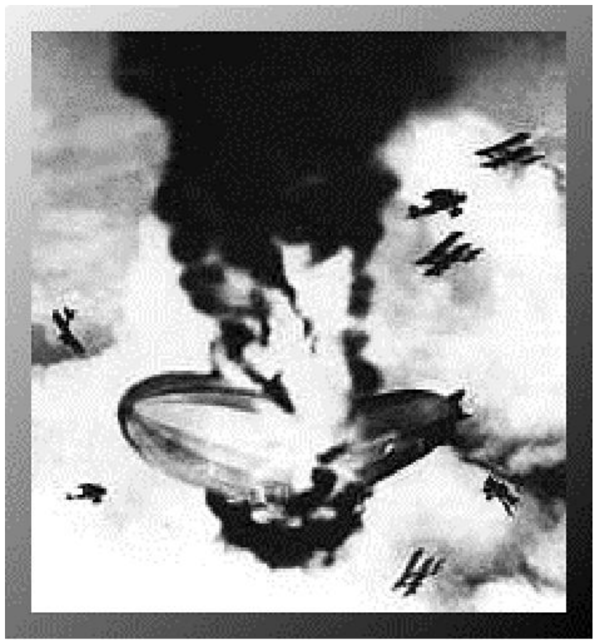

Figure 18. A swarm of biplanes bringing down a dirigible.

> The dirigibles were large and heavily armed, but their low airspeeds and lack of maneuverability made them vulnerable to the coordinated attacks of the more agile biplanes that took advantage of active lift.

5.4 CONCLUDING CHALLENGE

The problem with starting with simple autonomous agents is twofold. First, simple autonomous robotic systems *that are also useful* are difficult to define. Second, only with a clear promise of utility will operators be interested in adopting the new robotics products. The robotics development community needs to maintain the operator/ customer's interest in order to receive the necessary resources for development. The challenge then is to discover new ways to use simple self-interested (autonomous) robotic systems.

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APPENDIX A

RELEVANT DOD R&D PROGRAMS

Listed here are a sample (not exhaustive) of DoD R&D Programs that have potential to contribute capabilities to the VSW MCM UUV Program.

DARPA

Acoustic Microsensors, MTO/ATO, PM: Dr. Edgar J. Martinez

Adaptive Computing Systems (ACS), TTO, PM: Dr. William Phillips

Autonomous Negotiating Teams (ANT), ITO, PM: Dr. Janos Sztipanovits

Buoyant Cable Array Antenna (BCAA), ATO, PM: CAPT John Kamp

Controlled Biological and Biomimetic Systems, DSO, PM: Dr. Alan Rudolph, http://www.darpa.mil/dso/thrust/sp/Cbs/Programs.html

Distributed Robotics, MTO, PM: Dr. Elana Ethridge

Dog's Nose, ATO, PM: Dr. Thomas Altschuler, http://www.darpa.mil/ato/programs/UXO/index.html

Drag Reduction Program, ATO, PM: Dr. Parney Albright

Future Combat Systems (FCS), TTO, PM: http://www.darpa.mil/tto/fcs/index.html

Micro-Electromechanical Sensor (MEMS) Inertial Navigation System (INS), SPO, PM: Lt Col Gregory Vansuch

Mobile Autonomous Robot S/W, ITO, PM: Dr. Douglas Gage

Networked Embedded Software Technology (NEST), ITO, PM: Janos Sztipanovits, http://www.darpa.mil/ito/Solicitations.html

Robonaut (ARMS), ITO/NASA JSC, PM: http://www.jsc.nasa.gov/er_er/html/robonaut/robonaut.html

Software for Distributed Robotics (SDR), ITO, PM: Dr. Douglas Gage

Tactical Mobile Robots (TMR), ATO, PM: Douglas Dyer (May 2001), small man-portable robots

ONR

Gladiator Tactical Unmanned Ground Vehicle Program. Jeff Bradel, ONR 353, UGV Deputy Program Manager.

Mathematical, Computer, and Information Sciences Division
Autonomous Systems, PM: Dr. Behzad Kamgar-Parsi (via ONR web site)

Autonomous Systems, PM: Mr. James Valentine, (703) 588-0074 (via Mr. Jack Taylor)

Surveillance, Communications, and Electronic Combat Division
Target Tracking and Sensor Fusion, PM: Dr. Rabinder N. Madan

Ocean, Atmosphere, and Space Science and Technology Department
Organic MCM FNC, PM: Dr. Doug Todoroff
Shoaling Waves DRI,
Diver and UUV System and Technologies for VSW/SZ MCM Missions, Brian Glance ONR, 252 (703) 696-2596

Naval Expeditionary Warfare
Mine Counter Measures (Code 32): Organic Mine Hunting and Reconnaissance
POC: LTC Mark Miller

OSD Joint Robotics Program

UGV-S JPO, PM: LTC. Richard LeVan,

- Robotic Combat Support System (RCSS)
- Standardized Robotic System (SRS)
- Man-Portable Robotic System (MPRS)
- Tactical Unmanned Vehicle (TUV)
- Viking

PMS-EOD

- Basic Unexploded Ordnance Gathering System (BUGS)
- Remote Ordnance Neutralization System (RONS)

Air Force Research Laboratory, PM: Al Nease

- Robotic Ordnance Clearing System (ROCS)
- All-purpose Remote Transport System (ARTS)
- Advanced Force Protection Robotic System
- Next Generation Field Robotic System

Physical Security Equipment, PM: LTC Michael Bonheim

- Mobile Detection Assessment and Response System – Interior (MDARS-I)
- Mobile Detection Assessment and Response System – Exterior (MDARS-E)

Army Research Laboratory, PM: Chuck Shoemaker

- UGVTEE
- DEMO III, XUV

Aviation and Missile Command Research, Development and Engineering Center

- Joint Architecture for Unmanned Ground Systems JAUGS

NSF National Science Foundation

Robotics and Human Augmentation, CISE, IIS. PM: Vladimir Lumelsky, (703) 292-8980.

AFOSR Air Force Office of Scientific Research, http://www.afosr.af.mil/

APPENDIX B

ACRONYMS

AGC	automatic gain control
ATD	advanced technology demonstration
ATR	automatic target recognition
AUSS	autonomous underwater search system
AUV	autonomous underwater vehicle
BAA	broad agency announcement
BIPS	billion instructions per second
BIT	built-in test
C2	command and control
CONOPS	concept of operations
COTS	commercial off-the-shelf
DARPA	Defense Advanced Projects Agency
DGPS	differential GPS
DNA	deoxyribonucleic acid
DoD	Department of Defense
DUSD(S&T)	Deputy Under-Secretary of Defense for Science and Technology
EMI	electromagnetic interference
EMD	engineering and manufacturing development
EOD	explosive ordnance disposal
FCS	Future Combat System (Army program)
FIDO	field integrated design and operations
FLIR	forward-looking infrared

GPS	global positioning system
HMMWV	highly mobile multipurpose wheeled vehicle
ICD	interface control document
INS	inertial navigation system
IPT	integrated product team
IR	infrared
JAMC	joint amphibious mine countermeasures
JAUGS	joint architecture for unmanned ground systems
LAN	local area network
LMRS	Long-Term Mine Reconnaissance System
LOS	line of sight
MARS	Mobile Autonomous Robot Software (DARPA program)
M&S	modeling and simulation
MCM	mine counter measures
MDARS	Mobile Detection, Assessment, and Response System; I - interior, E - exterior
MOE	measures of effectiveness
MOP	measures of performance
MPRS	man portable robotic system
MS	milestone
NAS	National Academy of Sciences
NIST	National Institute of Standards and Technology
NTDR	near-term digital radio
OCU	operational control unit
ONI	Office of Naval Intelligence

ONR	Office of Naval Research
ORD	operational requirements document
PM	program manager
PPI	planned product improvement
R&D	research and development
REMUS	Remote Environmental Monitoring Unit-S
RF	radio frequency
RONS	Remote Ordnance Neutralization System
ROV	remotely operated vehicle
RSTA	reconnaissance, surveillance, and target acquisition
SCOWR	Scalable Coordination of Wireless Robots
SDR	software for distributed robotics (DARPA program)
SPAWAR	Space and Naval Warfare Systems Command
SSC San Diego	SPAWAR Systems Center, San Diego
STO	science and technology objectives
SZ	surf-zone
TIPS	trillion instructions per second
TMR	Tactical Mobile Robots (DARPA program)
TOV	teleoperated vehicle
UAV	unmanned air vehicle
UGV	unmanned ground vehicle
UUV	unmanned underwater vehicle
UXO	unexploded ordnance
VSW	very shallow water

WHOI	Woods Hole Oceanographic Institute
XUV	experimental unmanned vehicle (Demo III)

APPENDIX C

GLOSSARY

Agent	An entity engaged in an assigned task.
Automaticity	The state of a system when it is governed entirely by automatic processes
Autonomy	The state of a system when it's automatic processes are modulated by the confluence of both internal and external conditions
Baud	Unit of signaling speed equal to one code element per second
Cyborg	The product of the integration of artificial components with a natural organism. **[SAIC, 1997]**
Endogenous	Produced or generated within the agent
Exogenous	Provided to the agent from an external source
Learning	Long-term changes in response probabilities.

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